THE ELECTRIC PROPULSION OF SHIPS

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BY

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WITH 44 ILLUSTRATIONS

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PREFACE

Much attention is now being given to propositions relating to the electric propulsion of ships. A study of the circumstances reveals a remarkable accordance of means and requirements. The case may be briefly outlined as follows:—

The double transformation of energy in the form of work into energy in the form of electricity and again from electricity into work, may often, when the operations are on a large scale, be effected at an overall efficiency of 90 per cent. and even higher. In other words, at the cost of a loss of 10 per cent. in energy and of the initial and maintenance cost of the electrical machinery, engineers can interpose an electric drive between the prime mover and the machinery to be driven. The object of interposing an electric drive is to obtain advantages of flexibility which will permit of securing greater efficiency both in the prime mover and in the driven machinery, which, in the case of ship propulsion, is the propeller. Further great advantages relate to the superior means of control rendered available with electric drive.

In the case of ship propulsion, the prime mover has, until recently, almost always been a reciprocating engine. But during the last ten years, many ships have been fitted with steam turbines. As applied to ship propulsion, the steam turbine has not met with any approach to the almost unqualified success which has attended its use on land. This is chiefly because, in applying the steam turbine to ship propulsion, it has been necessary to adopt speeds several times lower than have been customary with land turbines. This has been necessary owing to the well-known circumstance that the efficiency attainable with the screw propeller is lower (for a given power) the higher the speed of revolutions. It was a realization of this circumstance, more than any other consideration, which first led to serious propositions for the electrical driving of large ships. But in the land station for electricity supply, the importance of operating

only just so much machinery at a time as shall enable the machinery in service to always be carrying its most economical load, has long been recognized by engineers, and it soon became apparent that the same consideration was of vast importance in the economical operation of ships. This is particularly the case with battleships, for at cruising speed these ships require only some 20 per cent. of the power which their machinery is capable of developing. Thus it has come to be recognized that a very important advantage of the electric drive as applied to ship propulsion, relates to the independence which it provides between the prime movers and the propellers. For instance, a triple-screw ship no longer requires to have just three engines. Four engines, or two, or some other number, may be more suitable. If four engines are employed, while only one may be required to be in service at cruising speed, nevertheless each of the three propellers will be driven by its own electric motor or motors. Thus it may readily be arranged that whatever machinery is in operation shall be carrying its most economical load.

Appreciation of the importance of this feature (which is exclusive to the electric drive and is not provided by any of the mechanical speed-reduction methods) has caused engineers to consider with increased interest the merits of the internal-combustion engine as a prime mover for ship propulsion, and it is seen (when employed in connection with the electric drive) to be a very promising alternative to the turbo-electric drive.

It would appear that the addition of the electric drive will save the situation for the steam turbine, and also for the internal combustion engine so far as relates to their application to ship propulsion. In addition to the attributes already mentioned, the electric drive at once provides for astern running without any of the complications, difficulties, and expense otherwise encountered in connection with astern running when the prime movers are other than reciprocating steam engines.

One of the most notable features of the electric drive relates to the greater precision afforded during stopping or quickly reversing or sharply altering the course of the ship. In these operations, no other means can approach the power and precision inherent to the electric drive. Dr. C. P. Steinmetz, Past President of the American Institute of Electrical Engineers, has recently stated (p. 1347 of the

Proc. Am. Inst. Elec. Engrs. for June, 1911), that "One of the most important advantages which the use of the electric drive holds out, is the possibility of a much more rapid stopping and reversing of the ship, more rapid than the steam turbine, or even the reciprocating engine, can give."

The British Admiralty stands alone in the adoption of the policy of equipping all battleships and cruisers with steam turbines. In the German Navy and in the American Navy, steam turbines have been employed to only a very limited extent, and, so far as relates to battleships and cruisers, appear to be regarded as inherently inferior to the piston engine for the purposes of marine propulsion. The inclusion of the feature of the electric drive will eliminate from the steam turbine proposition the inherent disadvantages which otherwise attend its use, and, in large sizes, will place it in the same position of unchallenged superiority over the reciprocating steam engine which it already occupies in land practice.

For constant-speed operation, the mechanical methods which are now being successfully exploited by Westinghouse, Parsons, and Föttinger are admirable. But for astern running, the last mentioned alone shares with electrical systems the advantage of dispensing with the necessity of reversing the prime mover, and (in the case of steam turbines) of providing auxiliary prime movers. None of these three systems comprise any feature endowing them with any such perfection of control in manœuvring or in prompt stopping, as can be provided by the electrical method. Moreover, it should not be overlooked that *all* ships are, on occasions, required, as when in crowded harbours and during foggy weather, to proceed at other than their normal speed. The mechanical systems cannot approach the electrical system in the matter of economy at other than maximum speed, and the superiority of the electrical system is very considerable for ships which must frequently proceed at speeds much below their maximum speed. For strictly constant-speed ships, a good case can, however, be made out for the use of mechanical gearing, as it should usually show higher efficiency and lower first cost than the equivalent in electrical machinery. As already mentioned, however, the mechanical method is at a disadvantage in requiring auxiliary turbines for reversing, and in affording a less powerful and exact command of the boat in all manœuvring operations.

In the above summary I have touched briefly upon many of the points involved; these and other points are given detailed consideration in the following pages. In connection with the study of the present treatise the reader may be interested to consult: Taylor's "Speed and Power of Ships" (Chapman & Hall, London, 1910); Stevens & Hobart's "Steam Turbine Engineering" (Whittaker & Co., London, 1906); Biles' "The Steam Turbine as Applied to Marine Purposes" (Charles Griffin & Co., London, 1906); and Neilson's "The Steam Turbine" (Longmans, Green & Co., London).

My thanks are due to my friend Mr. C. S. Colton for data which he kindly placed at my disposal relating to the Westinghouse-Melville-Macalpine reduction gearing.

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CHAPTER I

INTRODUCTORY

THE attention of engineers is being drawn with increasing frequency to the proposition of employing electrical apparatus as a component part of the machinery for propelling a ship. A good many plans of this sort have been proposed, and the vitality displayed by certain amongst them is itself indicative that there is a legitimate field for utilizing electrical machinery in propelling certain classes of ships. It seems to me that the wide differences of opinion which have been expressed in discussing the subject are largely attributable to a failure to recognize that while electrical methods may for one type of ship and for one set of conditions permit of obtaining very distinct commercial advantages, they may be utterly inappropriate for other types of ships and other conditions of service. In other words, it is impossible to generalize to the extent of stating unqualifiedly that it is or is not commercially advantageous to incorporate electrical apparatus in the machinery employed for propelling ships. But I consider that it can be definitely stated that for certain ships and services it is commercially advantageous to introduce electrical apparatus as a component part of the propulsive machinery, and that for other types of ship or other services it would be commercially disadvantageous.

The electrical engineer naturally experiences considerable diffidence in applying his special knowledge to such a question as ship

propulsion. In the early days of applying electrical methods to traction the electrical engineer's task related to improving upon horse-haulage, which quickly fell an easy prey when confronted with electro-mechanical methods of haulage. Nevertheless, electrical engineers cannot recall with entire complacency their pioneer efforts in this direction. While twenty years of engineering experience in applying on a large scale electrical methods of propelling vehicles have materially improved the status of the electrical engineering profession, nevertheless, the electrical engineer, in approaching the subject of ship propulsion with its highly developed methods of many years' standing, cannot with propriety attempt to do more than to place at the disposal of marine engineers and naval architects the special experience which he has acquired in applying electrical machinery to more or less remotely analogous propositions. Although the problems associated with the propulsion of vehicles are in many respects widely different from the problems encountered in ship propulsion, nevertheless the now well-assimilated data which electrical engineers have acquired in railway matters constitutes for them a tangible starting-point.

In the present treatise I endeavour to provide a bridge over which the marine engineer can make incursions into the electrical engineer's territory, familiarize himself in a certain measure with the electrical engineer's habits of thought, and return to his marine-engineering problems with a better comprehension of the reasons for the enthusiasm with which the electrical engineer regards the probability that there is a legitimate and fairly wide field for electrical machinery as a component part of the apparatus employed in propelling ships.

For my part, I have made serious efforts to acquire a reasonable knowledge of the broad aspects of the subject from the marine engineer's point of view. As an electrical engineer it would be futile for me to attempt to assimilate the marine engineer's data in more than a very rough way, but I have sought to do this and to place my results before electrical engineers in ways which, I trust, may be useful to them. I believe I shall fairly conclusively show that the incorporation of suitable electrical methods in ship propulsion is commercially advantageous in many cases, and I shall try to roughly outline the limitations; that is to say, I shall try to indicate the

boundary line between the appropriate and the inappropriate cases. With the wealth of data at the disposal of marine engineers, and with their close knowledge of many detail considerations, I am in hopes that they, with the further aid of the data which I contribute in this treatise, will be able to still more closely define these boundaries.

CHAPTER II

THE SIZE AND POWER OF SHIPS

THREE years ago (1908) an eminent marine engineer stated that "the average h.p. per annum produced in this country alone, for marine propulsion, was about 1,500,000," and he went on to say that 1,750,000 tons of steamships are annually constructed in this country. These aggregates yield us the rough result of an average of nearly 1 h.p. of engine capacity as corresponding to each ton of weight of steamship. It may be superfluous to point out that such a figure is only an average, and that while the little 45-ton *Turbinia* was equipped with 2000-h.p. turbines, or 45 h.p. per ton, the 38,000-ton *Lusitania* has only 68,000 h.p. of turbine capacity, or less than 2 h.p. per ton. An 18,000-ton Dreadnought requires (at full speed) a little more than 1 h.p. per ton, and the 27,500-ton *Carmania*, a little *less* than 1 h.p. per ton. The power required per ton of weight (*i.e.* per ton of displacement) increases rapidly with the speed to be provided, and decreases rapidly with increasing size of ship.

In a pamphlet entitled "The Cunard Turbine-driven Quadruple-screw Atlantic Liner *Mauretania*," published in 1907, from the offices of *Engineering* (London), there is given the table on page 5, which constitutes "a suggestive record of progress of Atlantic steaming at the end of each decade since the advent of the Cunard Company in 1840."

It may be taken as a rough but useful rule that for a given size of ship, the engine capacity required is approximately proportional to the cube of the speed. Thus, in the case of a 2000-ton ship, for the low speed of 12 knots, only some 1400 h.p. of engine capacity need be provided. But if the ship is designed for twice this speed,

i.e. for a speed of 24 knots, then (since the cube of 2 is equal to 8) there will be required an engine capacity of ($8 \times 1400 =$) about 11,000 h.p. Although such rules are only rough, they serve quite well, so far as relates to obtaining a sound idea of the subject, at any rate to the extent of knowing the correct general order of magnitude of the power required in any case.

Year.	Average speed in knots.	Displacement in tons.	I.H.P.	I.H.P. per ton of displacement.	Coal burned per 100 tons of displacement per nautical mile propelled.
1840	8·5	2,050	710	0·346	22 lbs.
1850	12·0	3,620	2,000	0·552	21 „
1860	12·5	7,130	3,600	0·505	18 „
1870	14·5	6,900	3,000	0·434	12 „
1880	15·2	9,900	6,300	0·626	10 „
1890	20·0	13,000	18,500	1·42	12 „
1900	23·5	23,620	40,000	1·69	12 „
1907	25·0	38,000	68,000	1·79	11 „

For ships of not widely different designs, one might employ the rule that for a given speed the power required varies as the two-thirds power of the displacement, and this may be useful on certain occasions, but it will here be preferable to consider the variations of the power required with vessels of various displacements in another way.

In the table on pp. 8 and 9, I have brought together from various sources, data of the displacement, speed, and power of a large number of ships equipped with steam turbines. Although the ships are all well known, the data as regards displacement, power, and speed, are often given slightly differently in different published descriptions, and it is almost out of the question to say in each case which data are most reliable. But in view of the large number of ships which I have brought together, my *average* results must almost necessarily be reasonably correct. I have confined the table to ships with turbine engines. This ensures the elimination of all but fairly modern designs. The collection of data in the table ranges from small yachts and torpedo craft up to cruisers, battleships, and trans-atlantic liners, and comprises the product of British, French, American, German, and Belgian shipbuilders. Nevertheless, the results show

a consistency which can only be accounted for as inevitably consequent upon fundamental principles to which the naval constructors in these various countries have learned to conform. The ships in the table are for speeds ranging from 37 knots down to 15 knots, and for displacements ranging from 45 tons (the *Turbinia*) up to 38,000 tons (the *Lusitania* and the *Mauretania*). The largest boat thus has 850 times the weight of the smallest. But the *Lusitania* has only 68,000 h.p., as against the *Turbinia's* 2000 h.p.; the larger power thus being only 34 times greater than the smaller, although the larger boat is 850 times heavier than the smaller. This is partly because the *Lusitania's* speed is only some 25 to 26 knots, as against the *Turbinia's* 34 knots, and partly because, for equal speeds, a very large boat, owing to its lesser resistance per ton, requires less power per ton than is required for a very small boat.

Column G of the table gives values for the indicated h.p. for a 20-knot boat of the same displacement, and has been derived from column F on the fairly-correct assumption that the necessary power is proportional to the cube of the speed. It has been necessary to reduce all the ships to a common basis as regards speed, as otherwise it would have been very unsatisfactory to attempt to extract from the table the results which I had in view. Column H contains the quotients of the values in columns G and B, *i.e.* the values in column H represent the power required per ton of displacement for 20-knot ships of various displacements.

In Fig. 1 I have plotted a curve with the values of the displacement (column B) as abscissæ and the corresponding values of the indicated h.p. per ton of displacement (for 20 knots), *i.e.* with the values of column H as ordinates. Since my heaviest vessel has 850 times the displacement of my lightest vessel, I have, in order to plot readable results in a single curve, altered the scale of abscissæ at 500, 2000, and 5000 tons. But, *in principle*, the curve is smooth from beginning to end; that is to say, had I retained throughout a single scale for the abscissæ, the three humps in the curve, occurring at 500, 2000, and 5000 tons, would have disappeared. But in the form in which I have drawn it, the curve is much more useful, owing to the greater facility with which it can be read.

From the curve in Fig. 1 a reasonably sufficient estimate may be made for the power required for a vessel of any given displacement

and speed. Thus, for an 18-knot 5000-ton ship, the procedure is as follows:—We first ascertain from the curve in Fig. 1 that for a 20-knot 5000-ton ship, 2·0 indicated h.p. per ton is required. Consequently, for an 18-knot 5000-ton ship there will be required—

$$[(\tfrac{18}{20})^3 \times 2{\cdot}0 =]1{\cdot}46 \text{ i.h.p. per ton,}$$

or a total of—

$$5000 \times 1{\cdot}46 = 7300 \text{ i.h.p.}$$

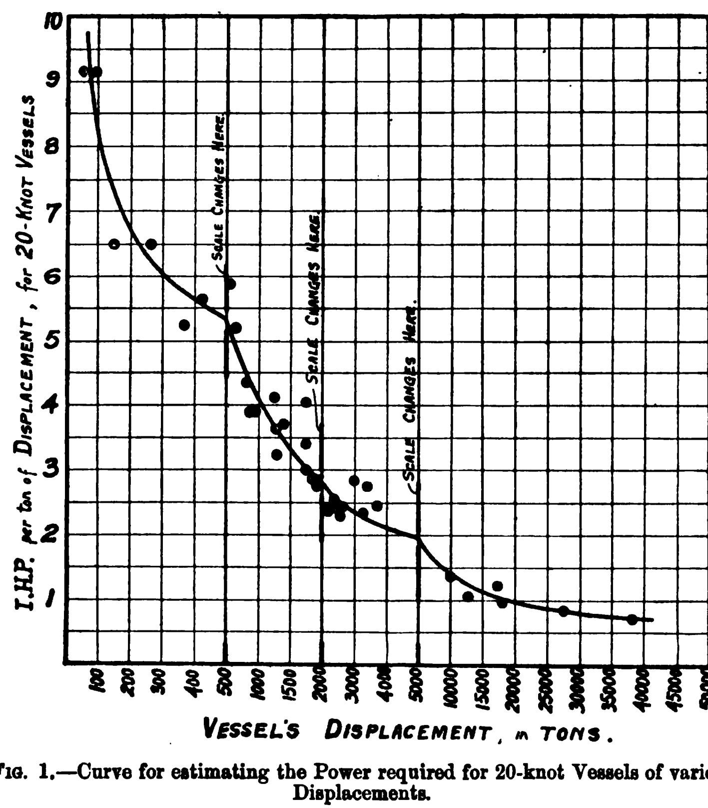


Fig. 1.—Curve for estimating the Power required for 20-knot Vessels of various Displacements.

The table on p. 12 contains the results of a large number of calculations made in the way just illustrated, and the results are plotted in the curves of Figs. 2 and 3.

We shall have occasion in subsequent chapters to refer back to

DISPLACEMENT, SPEED, AND POWER OF TURBINE-ENGINED SHIPS.

Designating number.	Displacement in tons.	Name of vessel.	Description of vessel.	Speed in knots.	Equivalent I.H.P. for speed in column E.	I.H.P. which would have been required for a 20-knot vessel of the same design and displacement.	I.H.P. per ton of displacement for a 20-knot vessel.
A	B	C	D	E	F	G	H
I.	44·5	"Turbinia"	Yacht	34·0	2,000	409	9·2
II.	94·6	"No. 293"	French torpedo boat	26·2	1,950	870	9·2
III.	150	"Tarantula"	Yacht	25·4	2,000	976	6 5
IV.	265	Torpedo boats of the British Admiralty's 1906 programme		26·5	4,000	1,720	6·5
V.	370	"Viper"	British destroyer	37·1	12,300	1,940	5·25
VI.	413	"S 125"	German torpedo boat	28·9	7,000	2,330	5·65
VII.	565	"Eden"	British destroyer	26·2	7,500	3,330	5·90
VIII.	643	"King Edward"	Clyde pleasure boats	20·5	3,500	3,360	5·23
IX.	800	"Queen Alexandra"	Clyde pleasure boats	21·6	4,400	3,500	4·37
X.	850	"Mohawk"	British destroyer	33·0	15.000	3,340	3·93
XI.	900	"Emerald"	Yacht	15·0	1,500	3,540	3·94
XII.	1,260	"Brighton"	Cross-channel boat of L. B. & S. C. Ry.	21·0	6,000	5,210	4·14
XIII.	1,300	"Lorena"	Yacht	18·0	3,500	4,750	3·65
XIV.	1,300	"Albion"	Yacht	15·0	1,800	4,250	3·26
XV.	1,360	"Dieppe"	Cross-channel boats, L. B. & S. C. Ry.	21 8	6,500	5,040	3·70
XVI.	1,750	"Queen"	Cross-channel boats, South-Eastern Railway	21·3	8,500	7,050	4·02
XVII.	1,750	"Onward"	Cross-channel boats, South-Eastern Railway	22·8	9,000	6,100	3·48
XVIII.	1,750	"Invicta"	Cross-channel boats, South-Eastern Railway	23·9	9,000	5,350	3·06

XIX.	1,900	"Princess Maud"	Clyde pleasure boat	20·7	6,000	5,450	2·86
XX.	1,950	"Kaiser"	Passenger boat of the Hamburg-American Line	20·6	6,000	5,500	2·82
XXI.	2,000	"Princess Elizabeth"	Cross-channel boat of Belgian State Railways	24·0	10,000	5,800	2·90
XXII.	2,150	"Londonderry"	Cross-channel boat of Midland Railway Company	22·3	7,200	5,200	2·42
XXIII.	2,200	"Lhassa"	Passenger boats of the British India Steam Navigation Company	18·1	4,000	5,400	2·46
XXIV.	2,200	"Linga"		18·1	4,000	5,400	2·46
XXV.	2,270	"Manxman"	Cross-channel boat of Midland Railway Company	23·0	9,000	5,900	2·60
XXVI.	2,400	"Viking"	Cross-channel boat of Isle of Man Steam Packet Company	23·5	9,500	5,850	2·46
XXVII.	2,500	"Loongana"	Cargo and passenger boats: Union S.S. Company of New Zealand	20·0	6,000	6,000	2·40
XXVIII.	2,680	"Bingera"	Cargo and passenger boats: British India Steam Navigation Company	17·5	4,500	6,660	2·48
XXIX.	3,000	"Amethyst"	British third-class cruiser	23·6	14,000	8,550	2·84
XXX.	3,250	"Lübeck"	German cruiser	23·9	13,000	7,750	2·38
XXXI.	3,300	"Boadicea"	British cruiser	25·0	18 000	9,200	2·78
XXXII.	3,750	"Salem"	Scout-cruisers of the U.S.A. Navy	24·0	16,000	9,300	2·48
XXXIII.	3,750	"Chester"		24·0	16,000	9,300	2·48
XXXIV.	10,000	"Creole"	Ocean mail boat	16·5	8,000	14,000	1·40
XXXV.	13,000	"Victorian"	Mercantile cruiser of the Allan Line	19·5	12,000	13,200	1·02
XXXVI.	17,250	"Invincible"	British cruiser	25·0	41,000	21,000	1·22
XXXVII.	17,900	"Dreadnought"	British battleship	21·0	23,000	17,300	0·97
XXXVIII.	27,500	"Carmania"	Mercantile cruisers of the Cunard Line	20·2	24,000	23,600	0·86
XXXIX.	38,000	"Lusitania"		25·0	68,000	28,000	0·74
XL.	38,000	"Mauretania"		25·0	68,000	28,000	0·74

the data in the table on p. 12, and also to consult the curves in Figs. 2 and 3. Since the table is confined to turbine ships, a contradiction is involved in stating the capacities in indicated h.p. In the case of steam turbines, the equivalent of the indicated h.p. of piston engines can only be inferred. Nevertheless, since it is so customary to thus state the capacity of marine engines, it has appeared preferable not to depart from it on this occasion.

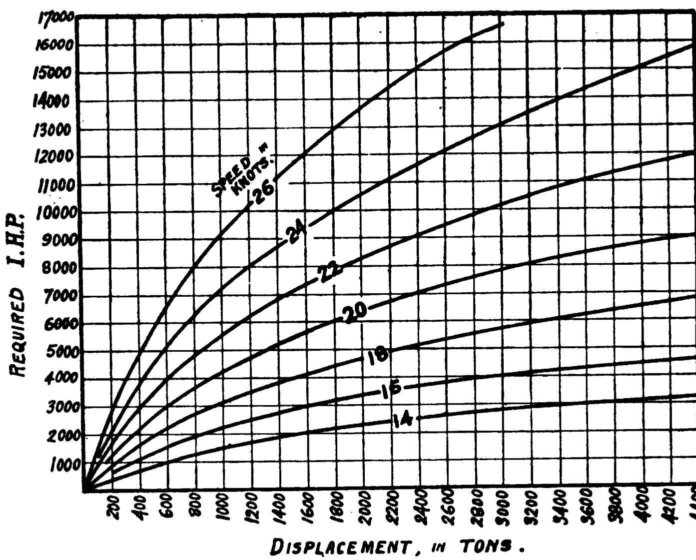


Fig. 2.—Horse-power required for Small Vessels of various Displacements and Speeds.

At p. 120 of vol. 52 (1910) of the *Transactions of the Institute of Naval Architects* there is a paper by Mr. Hope, entitled "The Application of the Internal-Combustion Engine to Fishing and Commercial Vessels." In his tables of data, the author employs the following symbols:—

$$\begin{aligned} V &= \text{Speed in knots,} \\ D &= \text{Displacement in tons,} \\ P &= \text{Horse-power of engines,} \\ L &= \text{Length at load water line,} \\ \frac{V}{\sqrt{L}} &= \text{Speed coefficient.} \end{aligned}$$

At p. 137 of the discussion of Mr. Hope's paper, Mr. H. C. Anstley says: "No simple formula can be devised which shall take in the varying elements of resistance and propulsive efficiency, but I venture to suggest the following, which I have tried in a number of cases, and

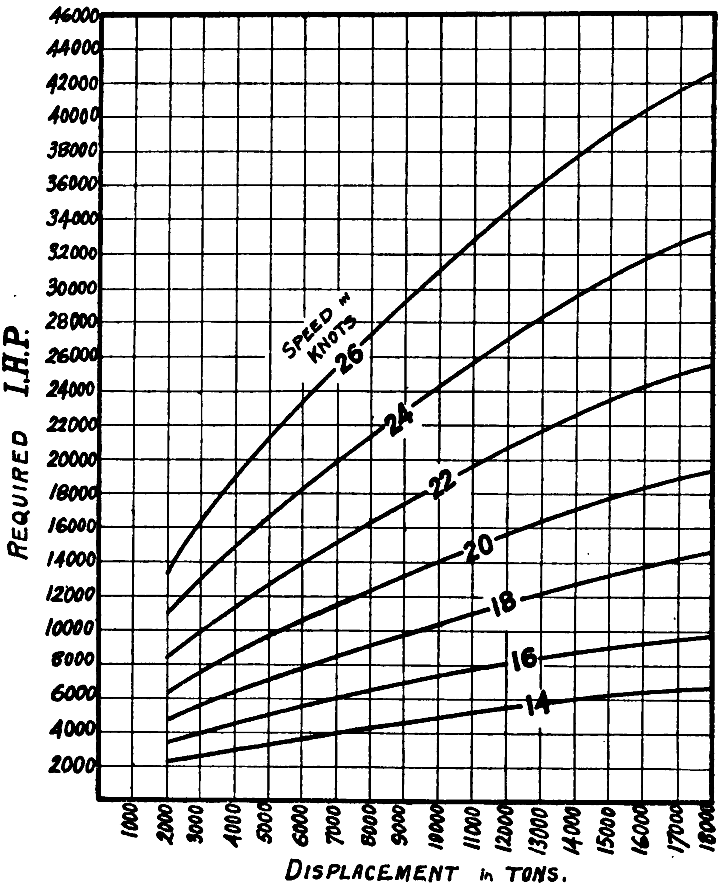


FIG. 3.—Horse-power required for Large Vessels of various Displacements and Speeds.

which yields fairly consistent results where the speed coefficient, $\frac{V}{\sqrt{L}}$, is greater than unity:—

$$P = \frac{D^{\frac{1}{2}}V^3}{C}$$

C varies from 50 to 55 when the power is indicated, or from 60 to 65 when it is shaft or brake h.p. It will be seen that this may be written—

$$\frac{P}{D} = \frac{1}{C} \times \frac{V^3}{D^{\frac{1}{3}}}$$

that is, the power per ton is proportional to $\frac{V^3}{D^{\frac{1}{3}}}$, and as, in similar vessels, D varies as L^3, it follows that in similar vessels the h.p. per ton is proportional to the cube of the speed coefficient. Where the

POWER REQUIRED FOR SHIPS OF VARIOUS DISPLACEMENTS AND SPEEDS.

Displacement in tons.	Indicated horse-power requiring to be provided for vessels of given displacements and given maximum speeds.						
	14 knots.	16 knots.	18 knots.	20 knots.	22 knots.	24 knots.	26 knots.
500	910	1,350	1,970	2,640	3,500	4,560	5,820
1,000	1,440	2,140	3,120	4,180	5,540	7,200	9,200
2,000	2,150	3,180	4,650	6,240	8,250	10,700	13,700
4,000	3,040	4,500	6,500	8,800	11,600	15,100	19,300
6,000	3,690	5,500	8,000	10,700	14,200	18,500	23,600
8,000	4,170	6,200	9,040	12,100	16,000	20,900	26,600
10,000	4,830	7,200	10,400	14,000	18,600	24,200	30,800
12,000	5,350	7,950	11,680	15,500	20,600	26,800	34,200
14,000	5,960	8,850	12,900	17,300	23,000	30,000	38,100
16,000	6,300	9,380	13,700	18,300	24,200	31,600	40,300
18,000	6,620	9,850	14,300	19,200	25,400	33,200	42,300
20,000	6,900	10,300	14,900	20,000	16,500	34,600	44,000

vessels are not similar, the speed and displacement must be used instead of the speed coefficient. The examples in the table on p. 13 will serve to show the fairly consistent results given by this formula in vessels of widely different type."

Mr. Hope, in his reply to the discussion, said (p. 139): "I am very pleased to see Mr. Anstley's suggested formula for ascertaining speed or power; it appears to give better results than any formula with which I am acquainted, while it has the merit of being extremely simple."

TABLE CONTAINING MR. ANSTLEY'S EXAMPLES OF THE APPLICATION OF HIS FORMULA.

Vessel.	Displacement. (D)	Shaft or brake h.p. (P)	Speed. (V)	Speed coefficient. $\frac{V}{\sqrt{L}}$	$\frac{D^{\frac{1}{2}}V^3}{P}$
Battleship	18,000	23,000	22	1·01	62·0
Cruiser	14,600	24,000 (27,000 indicated)	23	1·04	61·5
Torpedo boat destroyer .	560	6,000 (7,000 indicated)	25·6	1·70	61·7
56-ft. pinnace	18·5	210 (250 indicated)	14·7	1·95	64·6
Scotch ketch drifter . .	57	60	8	0·99	64·5
Oyster dredge launch . .	2·2	7	6·8	1·33	66·2
Mail and passenger boat.	107	300	12	1·06	59·5
Mail and passenger boat.	85	152	10·2	1·08	64 0

The Admiralty Coefficient.

A coefficient which has been widely used by naval constructors is the "Admiralty Displacement Coefficient."

This is the value of C in the following formula :—

$$C = \frac{D^{\frac{2}{3}} \times V^3}{\text{i.h.p.}}$$

To correspond with the above expression, I have arranged a formula for the thrust horse-power. It reads as follows :—

$$\text{Thrust h.p.} = \frac{D^{\frac{2}{3}} \times V^3}{410 + 0{\cdot}00070D}$$

A formula of this sort is amply sufficient for many purposes, but where much accuracy is required, the linear dimensions of the ship should be introduced into the estimates. In Taylor's "Speed and Power of Ships" (John Wiley and Sons, New York, 1910), there is given an "Extended Law of Comparison Coefficient," for which Taylor employs the letter N. Its value is—

$$N = \frac{I \times L^{\frac{1}{2}}}{V^3 \times D^{\frac{7}{6}}}$$

In the above formula, I denotes the indicated h.p. and L denotes the length in feet. V and D have the significance already employed in this treatise. Proceeding from this formula for N, it should be practicable, by the analysis of the known data of a large number of ships, to arrive at a formula for the thrust h.p. which would permit of very close estimates.

The estimation of the thrust h.p. presents no difficulty so far as relates to arriving at a result amply close enough to constitute a basis for deciding upon the engine capacity required. The chief doubtful factor is the propeller efficiency. In spite of a vast amount of theoretical and experimental investigation, it is quite a common experience that a ship's economy is improved by 10 and even 20 per cent. by modifications of or substitutions for the propellers originally fitted to the ship. This is often in spite of the fact that a large amount of preliminary investigation has been devoted to the particular case in hand. Although theoretical investigations may indicate propeller efficiencies of over 70 per cent., such efficiencies rarely materialize in actual practice. Of course, in a general way, the efficiency will be lower the higher the speed of revolution, but the number of screws, the power per screw, the displacement and the lines of the ship all affect the result. The propeller efficiency at the ship's normal speed will usually be between 50 per cent. and 60 per cent., often approaching (and even falling below) the former value for turbine-engined ships, and often being in the neighbourhood of the latter value for piston-engined ships.

But for propellers driven by electric motors, a reasonably favourable speed will, of course, be selected for the propellers, and also it should always then be practicable to defer completely to the naval architects' experience in all matters relating to the number of screws and their design and location. Consequently in calculations for *electrically*-propelled ships, no matter what type of prime mover be employed, it would appear reasonable to assume 60 per cent. for the propeller efficiency.

Thus, the output from the motors should be obtained by estimating the thrust h.p. from some suitable formula, such, for instance, as—

$$\text{Thrust h.p.} = \frac{D^{\frac{2}{3}} \times V^3}{410 + 0{\cdot}00070D}$$

Knowing the required thrust h.p., the next step is to estimate the shaft h.p. This step involves an acquaintance with the complex subject of propeller efficiency. Taylor's treatise deals with this at considerable length, but the conclusions are not reduced to anything very tangible. However, on p. 301, Taylor generalizes as follows—

"When an accumulation of power data is not available, it is generally safe, when using lines closely resembling those of the Standard Series, to assume a nominal efficiency of propulsion in the vicinity of 50 per cent. based upon *indicated* h.p. for reciprocating engines, and somewhat less, say 46 per cent., for the usual run of turbine jobs, but using *shaft* h.p. in this case. These average efficiencies are based upon the effective h.p. of the bare hull, and are sufficiently low to allow for the average run of appendages."

Let us consider the case of a ship requiring a thrust h.p. of 10,000. Applying the rough generalization given above by Taylor, a piston-engine ship would require to have engines of—

$$\frac{10{,}000}{0{\cdot}50} = 20{,}000 \text{ i.h.p.}$$

A turbine-engined ship would require to have turbines of—

$$\frac{10{,}000}{0{\cdot}46} = 21{,}800 \textit{ shaft} \text{ h.p.}$$

or say—

$$\frac{21{,}800}{0{\cdot}95} = 22{,}900 \text{ i.h.p.}$$

Thus, Taylor's rough generalization is based on an overall efficiency of—

$$\tfrac{10000}{20000} \times 100 = 50 \text{ per cent. for the piston-engined ship.}$$

And of only—

$$\tfrac{10000}{22900} \times 100 = 43{\cdot}6 \text{ per cent. for the turbine-engined ship.}$$

Or (since $\tfrac{22900}{20000} = 1{\cdot}145$) it follows that 14·5 per cent. more engine capacity is required in "the usual run of turbine jobs" than for the equivalent ship employing piston engines.

CHAPTER III

THE ENERGY REQUIRED PER TON-MILE IN PROPELLING SHIPS AT CONSTANT SPEED

WITH engines of 100 per cent. thermodynamic efficiency,[1] and with frictionless shafts, and with propellers of 100 per cent. efficiency, the indicated h.p. would be identical with the propulsive h.p. But the efficiencies of propellers in turbine-driven vessels usually range from 40 to 70 per cent., generally being nearer the lower of the above two values. Taking 55 per cent. as a representative value (just to fix ideas), and taking 90 per cent. as the efficiency from the cylinder of the turbine (or engine) to the propeller, the propulsive h.p. is just about half the indicated h.p. (for $0{\cdot}55 \times 0{\cdot}90 = 0{\cdot}495$). In actual practice, there will be large variations from this value of the ratio, but it is nevertheless a very useful figure to bear in mind at this stage.

In traction problems on land, electrical engineers often find it very convenient to base their calculations on the energy consumption in watt-hours per ton-mile, and the same general procedure is also useful in connection with certain ship-propulsion calculations. It must be remembered that the nautical mile is 6080 ft. (1850 metres), or 1·152 times the length of the statute mile (5280 ft., or 1609 metres). Throughout this book the word "mile" will be employed to mean the nautical mile of 6080 ft. (1850 metres).

Let us consider the case of a 1000-ton 16-knot boat, and let us ascertain its friction when proceding at a constant speed of 16 knots. From Fig. 2, on p. 10, we find that some 2150 i.h.p. will be required of the engines. The propellers will deliver some $(0{\cdot}50 \times 2150 =)$ 1075 propulsive h.p. In one hour the energy expended in overcoming the

[1] For a discussion of the "thermodynamic" efficiency, see p. 14 of the Author's "Heavy Electrical Engineering" (Constable, London).

friction[1] of the ship and of the surrounding media, due to the ship's passage through the water and air, will be 1075 h.p.-hours, or (1075 × 746 =) 803,000 watt-hours.

During one hour the ship will have travelled a distance of 16 nautical miles. Consequently the friction per ton-mile amounts to—

$$\frac{803{,}000}{16 \times 1000} = 50 \text{ w.-hr.}$$

To make similar calculations for a 10,000-ton 16-knot ship we

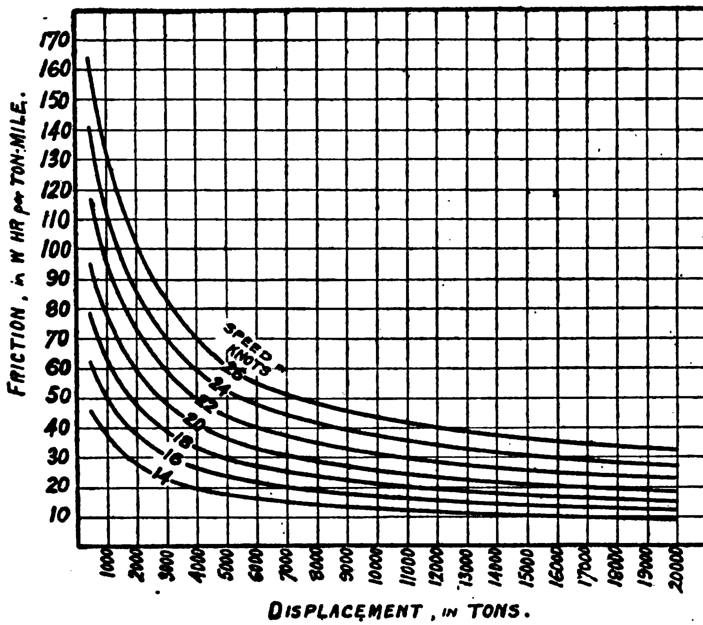


FIG. 4.—Friction of Ships of various Displacements and Speeds.

should consult Fig. 3, from which we should find some 7200 i.h.p. to be required. The friction per ton-mile amounts in this case to—

$$\frac{0{\cdot}5 \times 7200 \times 746}{16 \times 10{,}000} = 16{\cdot}8 \text{ w.-hr.}$$

It thus appears that in overcoming the friction of these 16-knot

[1] The term "friction" is to be taken as including the energy of the wave motion set up by the ship by its passage through the water. See p. 73 of Taylor's "Speed and Power of Ships" (Chapman & Hall, London, 1910).

ships, the ten times larger ship only requires, per ton of weight, one-third of the power which is required per ton of weight by the smaller ship at the same speed.

The very rough assumption as to the ratio of the propulsive h.p. to the indicated h.p., *i.e.* 0·50, precludes any considerable accuracy, nevertheless the results would appear to be as near the mark as can be obtained by any generally-applicable and simple method. So I have considered it of interest to apply the method to the range ot ships covered by the curves of Figs. 2 and 3, and the results are set forth in the following table. The results in the table are plotted in the curves in Fig. 4, on p. 17.

ROUGH VALUES FOR THE FRICTION OF SHIPS EXPRESSED IN W.-HR. PER TON-MILE.

Displacement in tons.	Friction in w.-hr. per ton-mile, for ships of the speeds at the heads of the vertical columns.						
	14 knots.	16 knots.	18 knots.	20 knots.	22 knots.	24 knots.	26 knots.
500	47·0	61·6	78·3	96·5	117·0	139·0	163·0
1,000	37·8	49·7	63·1	77·7	94·2	112·0	131·0
2,000	29·0	38·0	48·4	59·5	72·0	86·0	100·0
4,000	20·0	26·2	33·3	41·0	49·6	59·0	69·4
6,000	16·2	21·3	27·1	33·3	40·3	48·0	56·4
8,000	13·8	18·2	23·1	28·4	34·4	41·0	48·0
10,000	12·7	16·7	21·2	26·1	31·6	37·6	44·2
12,000	11·7	15·4	19·5	24·0	29·0	34·6	40·5
14,000	11·1	14·6	18·5	22·8	27·6	32·8	38·6
16,000	10·3	13·6	17·2	21·2	25·6	30·6	35·8
18,000	9·7	12·7	16·2	19·9	24·0	28·6	33·6
20,000	9·3	12·2	15·5	19·0	23·0	27·4	32·1

CHAPTER IV

THE FRICTIONAL RESISTANCE[1] *OF SHIPS*

FROM the table on p. 18, it is seen that the energy required to overcome the friction of a 500-ton ship proceeding at a constant speed of 20 knots is 96·5 w.-hr. per ton-mile. One w.-hr. is equal to 367 kilogram-metres. Consequently the friction may also be expressed as (96·5 × 367 =) 35,400 kg.-m. per ton-mile. A (nautical) mile is equal to 1850 metres. Since the energy consumed in friction while the ship travels 1850 metres is 35400 kg.-m. per ton, the frictional resistance is—

$$\frac{35{,}400}{1850} = 19{\cdot}1 \text{ kg. per ton.}^{2}$$

The values in the table on p. 20 have been worked out in this way, and they are plotted in Fig. 5. In Fig. 6 are plotted two groups of curves. The upper group relates to the frictional resistance in kg. per ton for ships of 2000, 6000, and 20,000 tons displacement, and the lower group relates to the frictional resistance of trains of 50 tons and 800 tons weight. It is seen that at any reasonably high

[1] In the term "frictional resistance" I also include the frictional loss in the wave motion occasioned by the ship.

[2] In this instance, metric units are much to be preferred. For since one kilogram is one-thousandth of a metric ton, it follows from the statement that the frictional resistance is 19 kilograms per ton, that the coefficient of friction is 0·019. But if it were stated that the frictional resistance is 41·8 lbs. per metric ton, the calculation of the coefficient of friction requires the following step:—

$$\text{Coeff. of friction} = \frac{41{\cdot}8}{2205} = 0{\cdot}019.$$

But in Figs. 5 and 6 the corresponding values of the frictional resistance in pounds per ton have also been given, consequently no inconvenience is occasioned to the reader who prefers this unit.

speed the friction coefficient is much higher for ships, but that at low speeds the friction coefficient of large ships comes down to the same range of values as that of trains.

FRICTIONAL RESISTANCE OF SHIPS OF VARIOUS DISPLACEMENTS AND SPEEDS.

Displacement.	Frictional resistance in kg. per ton for ships of the speeds at the heads of the vertical columns.						
	14 knots.	16 knots.	18 knots.	20 knots.	22 knots.	24 knots.	26 knots.
500	9·3	12·3	15·5	19·1	23·1	27·5	32·3
1,000	7·5	9·8	12·4	15·4	18·6	22·1	26·0
2,000	5·7	7·4	9·5	11·8	14·2	17·0	19·8
4,000	4·0	5·2	6·6	8·1	9·8	11·6	13·7
6,000	3·20	4·2	5·4	6·6	8·0	9·5	11·1
8,000	2·73	3·55	4·5	5·6	6·8	8·1	9·5
10,000	2·51	3·27	4·2	5·2	6·2	7·4	8·8
12,000	2·31	3·00	3·9	4·8	5·7	6·8	8·0
14,000	2·19	2·85	3·62	4·5	5·4	6·5	7·6
16,000	2·04	2·66	3·36	4·2	5·1	6·1	7·1
18,000	1·92	2·50	3·15	4·0	4·7	5·7	6·7
20,000	1·84	2·40	3·03	3·8	4·5	5·4	6·4

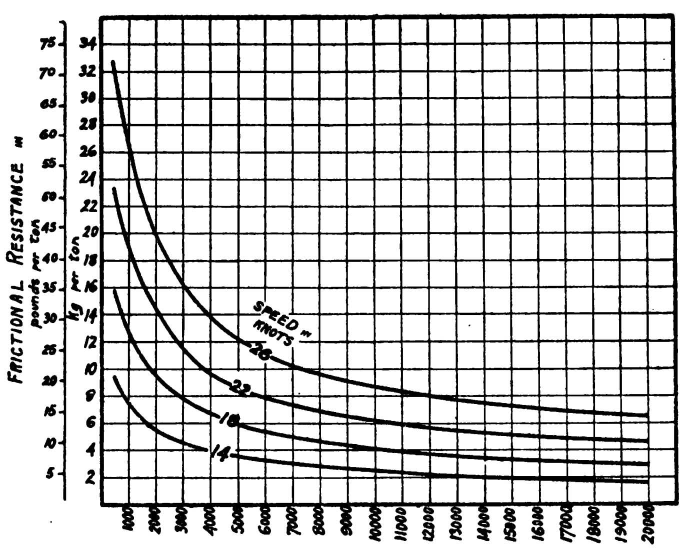


FIG. 5.—Frictional Resistance of Ships of various Displacements and Speeds.

When the frictional resistance is (as in the case of the 500-ton 20-knot ship) 19·1 kg. per ton, then, since there are 1000 kg. in 1 ton, the coefficient of friction is 0·019. For ships of a given displacement, the frictional resistance increases as the square of the speed. Thus, in the above table (p. 20) we see that for a 500-ton 14-knot boat the frictional resistance is 9·3 kg. per ton. Conse-

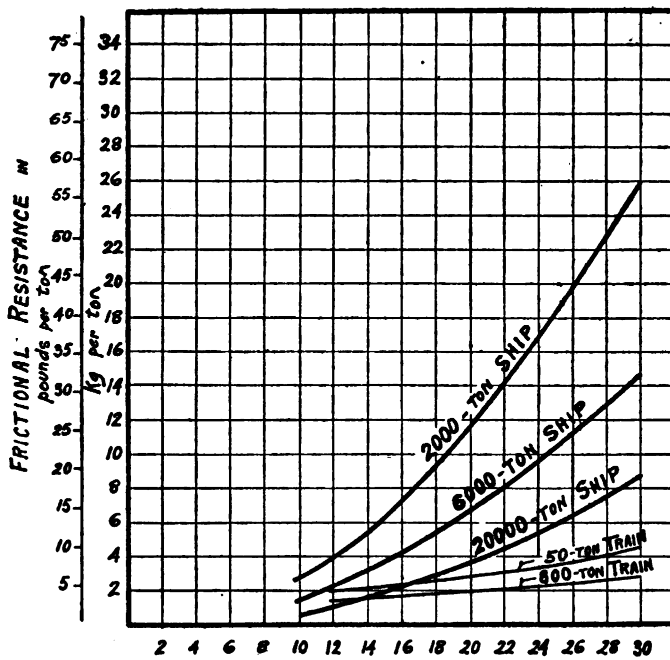


Fig. 6.—Frictional Resistance of Ships and Trains when travelling at Constant Speeds.

quently for a 28-knot boat of 500 tons displacement, the frictional resistance (assuming the same or equivalent lines in each case) will be $[(\frac{28}{14})^2 \times 9{\cdot}3 =]\,37$ kg. per ton. The coefficient of friction in the latter case is 0·037.

CHAPTER V

THE MOMENTUM OF SHIPS

In order to bring a ship from rest up to a speed of S knots, there must be imparted to each ton of weight of the ship an amount of energy which, expressed in w.-hr., we may denote by E, and which may be obtained by the following formula:—

$$E = 0{\cdot}0368S^2.$$

This is the ship's energy of *translational* momentum. The additional momentum of the *rotating* parts is, in the case of ships, too small a percentage to require to be taken into account. It may be of interest to the reader to mention that in the case of trains, the energy of rotational momentum often amounts to over 10 per cent. of the energy of translational momentum.[1]

In considering electrical methods of propelling ships we must not overlook the large amounts of energy involved in manœuvring the ship. Suppose a 30,000-ton ship is proceeding at a speed of 25 knots. Her momentum is—

$$0{\cdot}0368 \times 25^2 \times 30{,}000 = 689{,}000 \text{ w.-hr.}$$

or

$$\frac{689{,}000}{746} = 923 \text{ h.p.-hr.}$$

It has (neglecting the ship's friction) required a matter of—

$$\frac{923}{0{\cdot}5} = 1846 \text{ i.h.p.-hr.}$$

to bring the vessel from rest up to the speed of 25 knots. To do

[1] See p. 29 of "Electric Trains" (Harper & Bros., 1910).

this in 5 min. would have required the engines to develop an average of

$$\tfrac{60}{5} \times 1846 = 22{,}100 \text{ i.h.p.}$$

If the speed were imparted to the ship at a uniform rate, and if the overall efficiency remained uniform at all speeds, then the indicated h.p. of the engines would have increased uniformly from 0 at the instant of starting, up to 44,200 h.p. at the instant of arriving at a speed of 25 knots. Including the ship's friction, and making allowance for the very low efficiency at low speeds, it is probable that the work done by the engines in bringing this 30,000-ton ship from rest up to a speed of 25 knots would be of the order of 3000 i.h.p.-hr.

I mention these data since I am of opinion that it indicates and illustrates the importance of providing, in electrical propulsion equipments, for good torque for the entire range of speeds. It is customary to assert that the starting of a ship is a task for which the squirrel-cage induction motor is thoroughly appropriate, since the *friction* of a ship increases as the cube of the speed, and is exceedingly low during the first moments after starting. While the *friction* certainly is low at low speeds, nevertheless considerable torque is required in order to accelerate the ship, *i.e.* in order to impart to it the energy of translational momentum. In a sense the squirrel-cage motor is appropriate, for while it has but slight starting torque, the propeller and the water may be regarded as constituting a sort of flexible coupling, enabling the motor to run through its weak-torque stages before it tackles its job. Nevertheless, it is very important not to overlook the enormous part played in providing momentum to the ship.

If we bring this ship up to a speed of 25 knots in 5 minutes the acceleration is only—

$$\frac{25}{5 \times 60} = 0{\cdot}083 \text{ knot per second,}$$

or, since—

$$1 \text{ knot} = 1{\cdot}69 \text{ feet per second,}$$

the acceleration is—

$$1{\cdot}69 \times 0{\cdot}083 = 0{\cdot}14 \text{ foot per second per second.}$$

This is only a matter of one-quarter to one-half the acceleration customarily employed with steam railway passenger trains, and is only one-tenth of the acceleration of an urban passenger train operated by electricity. It would appear that a first essential of electrical equipment for ship propulsion should be the provision of increased facility for manœuvring the ship.

Let us consider that our ship, travelling with a speed of 25 knots, is brought to rest in 5 minutes, the deceleration being of the uniform value of—

$$0{\cdot}14 \text{ foot per second per second.}$$

The average speed during these 5 minutes is 12·5 knots, and the distance travelled is—

$$12{\cdot}5 \times \tfrac{5}{60} \times 6080 = 6330 \text{ feet.}$$

Obviously, then, the motors should be of a type and the generating plant of an aggregate power, capable, in emergencies, of bringing such a ship to rest in very much less than 5 minutes.

So far as regards astern running, turbine-engined ships are notoriously inferior to piston-engined ships. In the *Times* "Engineering Supplement" for Sept. 21, 1910, an article deals with a report of the United States Navy, contrasting the piston-engined scout-cruiser *Birmingham* with the turbine-engined scout-cruisers *Salem* and *Chester*. The following is quoted from this article:—"The report states that with reciprocating engines, a backing power about equal to the ahead power is afforded, without additional weight other than that of the astern eccentrics, rods and links. With turbines, backing power requires additional prime movers, and it is therefore necessary to restrict the equipment to the power actually demanded by tactical considerations, and this power is estimated to be 40 per cent. of the ahead power. With this limitation, the backing trials were carried out at speeds of 10, 16, and 24 knots, and it was found that at all speeds, the reciprocating engines provided better backing power than the Curtis turbines, and that the Curtis type of turbine is, in this respect, superior to the Parsons type."

The great inferiority of the turbine, as regards the manœuvring power of a ship, is said to have once drawn from a leading official

in the German Navy the remark that he "hoped all the ships of the enemies of Germany would have turbines." In the course of this little treatise, however, it will become apparent that by the interposition of a suitable system of electric transmission, a turbine-engined boat can have manœuvring capacity greatly excelling that of any warship at present afloat, and I am of the decided opinion that this should be regarded as one of the very most important advantages which can be obtained by employing electric propulsion. It is an established fact that turbine-engined ships are much inferior to piston-engined ships as regards manœuvring capacity. But by interposing electrical machinery between the turbines and the propellers, the turbine-engined ships will no longer be the object of reproach as regards any inferiority in manœuvring capacity, and the advocates of applying steam turbines for a wide range of ships can hardly afford to ignore the strength given to their case by incorporating the feature of electric propulsion. For mercantile vessels proceeding in fog, and for warships in many circumstances, it can hardly be said that ability to pull up sharply, or to reverse or to deviate abruptly from her course, are features of minor importance. It does not suffice to say that the reverse-turbine proposition is equal to *most* contingencies. The best means available should be adopted. With direct drive, the piston-engine surpasses the turbine, but the indirect drive by means of electrical machinery is capable of providing still greater manœuvring capacity.

As an instance of the manœuvring capacity of the largest turbine-engined ships, it is of interest to quote from Mr. Thomas Bell's paper on the *Lusitania* (see p. 492 of *Engineering*, for April 10, 1908): "In a fast passenger liner such as the *Lusitania*, it is of the utmost importance that the manœuvring capabilities should leave nothing to be desired, and to demonstrate the possibilities of the ship in this respect, various trials were made, the most important being the following:—

"*Stopping Trial.*—The ship was run on the Skelmorlie measured mile at a speed of 22·8 knots, the average revolutions of the propellor being 166 per minute. On entering the mile, the engine-room telegraphs were rung to 'Full speed astern'; the ship was brought to rest in 3 minutes 55 seconds, the distance run being about three-quarters of a mile, or about six times the length of the ship.

During this trial the boilers in the three after boiler-rooms only were in use, and the initial pressure at the astern turbines was about 90 lbs.

"*Circle Trials.*—With the ship initially on a straight course and the turbines running at an average speed of 180 revolutions per minute, the steering wheel was put hard over in 17 seconds. The tiller went over to 35 degrees in 20 seconds, and the vessel made a complete circle in 5 minutes 50 seconds, the average revolutions coming down at the completion of the circle to 70 per cent. of the rate at the commencement. The resulting circular path was approximately 1000 yards, or four lengths of the ship, in diameter. This manœuvre was made both under starboard and port helm, with very closely confirmatory results.

"Going astern, with the inner propellers running at a uniform rate of 136 revolutions per minute, and under full helm, resulted in half-circles being made in an average time of 6 minutes 45 seconds."

CHAPTER VI

THE SPEED AND EFFICIENCY OF PROPELLERS

UP to a few years ago the standard practice on all large ships was to drive the propellers from slow-speed engines. The design and construction of propellers for obtaining the best results at low speeds has been the subject of a vast amount of study and experimental investigation. Nevertheless, the efficiency even of the best slow-speed propellers is low. It is not a definitely known quantity, as there is no satisfactory means of measuring it under actual service conditions. We find the most eminent authorities in wide disagreement as to the efficiency of propellers. Thus, Mr. E. M. Speakman, in a contribution to the discussion of a paper read before the Institute of Engineers and Shipbuilders in Scotland on February 18, 1908, writes: "He did not know why there was a popular idea that the average efficiency of reciprocating engines' propellers, or *any* propellers for that matter, should reach such a value,[1] because he had not come across any experiments or results of trials of efficiency, on actual ships, that justified the idea of 70 per cent. He thought it was more likely to lie between 62 and 64 per cent. for a good propeller." On the same occasion, Professor J. H. Biles (Professor of Naval Architecture at Glasgow University) expressed himself as follows:—"Mr. Speakman had said that he doubted the efficiency of the propellers being as high as 70 per cent., and he did not know of any records of experiments showing any such results, but Mr. Taylor's book gave results as high as 80 per cent." (Mr. Speakman: "There was no sea-going data.") Professor Biles: "There were records which would show higher than 70 per cent. at sea. Of course, it was a matter of opinion as to what was the real relation of the efficiency at sea and the efficiency in model propellers."

[1] 70 per cent.

Admiral Oram, Engineer-in-Chief of the Navy, in his Presidential Address at the Junior Institution of Engineers, on November 16, 1909, made the following statement:—"It must be remembered that the efficiency now obtained with a slower-running propeller has been the result of many years' experience. The early turbine propellers had low efficiencies; experience has enabled these to be increased, but they do not yet reach the figures obtained with the slower-running reciprocating engines. There is no doubt that as more experience with small fast-running propellers for such large powers as have only been recently introduced is obtained, the efficiency of the latter will be still further improved. In particular cases, such as in the large cruisers of the *Invincible* class, there has been no falling-off in propeller efficiency of the faster-running screws from efficiencies obtained in the slow-revolution screws of older cruisers."[1]

In a comment upon this statement of Admiral Oram, Sir William White (on the occasion of the discussion of a paper by Mr. Mayor read at the Institution of Civil Engineers in 1909) said: "Of course, very much had to be learned about the screw propeller; screw propellers had been at work for fifty or sixty years, but it was simply a fact that the problem had not yet been mastered. Discoveries were continually being made. The variables affecting the efficiency were so numerous that it was almost impossible to lay down a general law, and it was only by experiment and analysis that it had been possible to make the considerable advances already made. So in regard to the quick-running propeller; the propeller in association with the turbine must run quickly as compared with the propeller associated with the reciprocating engine and large powers. A little time had to be allowed to gain experience in order that efficiency might be advanced. The conclusion he had endeavoured to state, which Admiral Oram endorsed, was also endorsed by some of the most able investigators on the Continent. Only a few days ago he had been reading the result of investigations made by a German, Dr. Flamm, who absolutely accepted the same conclusion. The great series of experiments made on a model launch, electrically propelled, in connection with deciding upon the propeller arrangements for the great Cunard steamships, had yielded an immense amount of information, and results had been obtained

[1] *Journal of the Junior Institution of Engineers*, vol. 20, p. 127.

which *contradicted the anticipations* of most of the people concerned, with regard to the efficiency of propellers of various forms, in various positions, and running at various rates. The problem, therefore, in his judgment, must not be stated in the bald terms—which he thought the author (Mr. Mavor) himself had rather accepted—that a quick-running propeller must of necessity be an inefficient propeller. He granted that in many cases it had been so. It need not be so always, and in that direction further investigation must proceed."

In the *Times* "Engineering Supplement" for December 1, 1909, is printed an extract from a prospectus by Mr. George Westinghouse, in which the use of double-helical gearing is advocated for adapting high-speed turbines to slow-speed propellers. In the year 1904, Mr. Westinghouse obtained from Rear-Admiral Melville, of the United States Navy, and Mr. Macalpine, a joint report on the status of the steam turbine as applied to the propulsion of ships. They stated in this report "that if a means could be found of reconciling in a practical manner the necessary high speed of revolution of the turbine with the comparatively low rate of revolution required by an efficient propeller, the turbine would practically wipe out the reciprocating engine for the propulsion of ships." In the *Times* article Mr. Westinghouse expresses the opinion that in the *Mauretania* and the *Lusitania* "it is hardly possible that the propeller efficiency exceeds 55 per cent." He states that: "At a lower speed of revolution, well within the capabilities of the reduction gear, a propeller could be made that would have an efficiency of not less than 65 per cent."

In the *Times* "Engineering Supplement" for December 22, 1909, there is an article by Sir William White, in which he contrasts the performance of the *Mauretania* in 1909 with its performance during its first eight months in service (1907 and 1908). Between these two periods the *Mauretania* had undergone "an extensive refit, rendered necessary by accidents to two of her propellers." Various modifications in the design and arrangement of her propellers were made on that occasion. Thus, "two four-bladed screws were placed forward, the two three-bladed screws originally fitted being retained in the aftermost positions." [1] Sir William White states that while the change was made primarily for the purpose of securing greater

[1] For the arrangement of the screws on the *Lusitania* and *Mauretania*, see Fig. 7, on p. 31, and also Fig. 9, on the Plate facing p. 42.

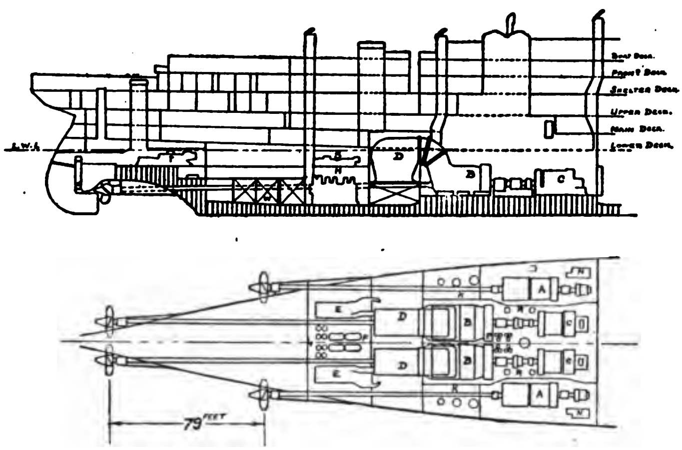
freedom from vibration (and has accomplished this purpose), "it has undoubtedly been accompanied by an increase in the propulsive efficiency; and the improved performance of the *Lusitania*—since propellers have been fitted similar to those of the *Mauretania*—confirms this view."

To indicate the extent of the net improvement in the *Mauretania's* performance, of which the greatest part may be ascribed to "enlarged experience in the management of the propelling apparatus, and especially in the organization of the stokehold arrangements," Sir William White cites the following data:—"The best westward trip of the *Mauretania* up to May, 1908, gave an average speed of 24·86 knots; the best trip in 1909 gave an average of 26·06 knots. To this increase in speed corresponds an increase in h.p. of about 25 per cent., on the supposition that the propeller efficiency remained the same. It is known from experimental investigations that the changes made in the propellers have not resulted in an improved efficiency approaching one-half of that figure. This statement is made with full recognition of the fact that *in many instances changes in propellers have resulted in quite as great increase in speed* as has been realized in the *Mauretania*, but in these instances the conditions were quite different. It is not improbable that further experience may lead to still further advance in speed and economy of working in the big ships, and that even-more-efficient propellers may be discovered. Reports have been circulated to the effect that new four-bladed propellers are to be fitted aft as well as forward in the *Mauretania*. If this is done, the results will be of great interest to shipowners, naval architects, and marine engineers."

Fig. 7 shows the relative positions of the inner and outer propellers of the *Lusitania*. The inner propellers (those shown in the illustration are the original three-bladed propellers) are 79 feet aft of the outer propellers. Each of the outer propellers is driven by a high-pressure turbine, and each of the inner propellers by a low-pressure turbine. Each of the inner propellers is also provided with a reversing turbine. These reversing turbines are arranged in independent casings.

At 25 knots the speed of the propellers is about 190 r.p.m. As indicated on p. 29, Mr. Westinghouse has stated that "it is hardly possible that the propeller efficiency exceeds 55 per cent." Mr.

Westinghouse estimates that, "at a lower speed of revolution well within the capabilities of the Melville-Macalpine reduction gear, a propeller could be made that would have an efficiency of not less than 65 per cent." In a paper by Mr. Thomas Bell, read before the Institution of Naval Architects, and published in *Engineering* for April 10, 1908 (p. 490), the power required to propel the *Lusitania* at a speed of 25 knots was given as some 65,000 shaft h.p., and the propeller efficiency was given as 48 per cent. under these conditions.



A	High Press. Turbine	F	Main Air Pumps	P	Main & Auxil. Feed Pumps.
B	Low " "	G	Dry Air Pumps	R	Hotwell Pumps.
C	Astern "	H	Pump Room.	S	Turbo-Generator.
D	Main Condenser.	K	Evaporator Room	T	Steering Engine.
E	Main Circulating Pumps	N	Auxiliary Cond^r.	W	Fresh water Tanks.

Fig. 7.—Elevation and Plan of Engine-room of the turbine-engined Mercantile Cruiser *Lusitania* of the Cunard Line.

If we make the rough assumption that the propeller efficiency as *now*[1] equipped is 55 per cent., then the power required for a speed of 25 knots is now—

$$\tfrac{48}{55} \times 65{,}000 = 56{,}600 \text{ shaft h.p.},$$

or some—

$$\tfrac{56600}{4} = 14{,}100 \text{ h.p. for each one of the four shafts.}$$

The output from each propeller is thus some—

$$14100 \times 0{\cdot}55 = 7800 \text{ thrust h.p.}$$

[1] See Sir William White's remarks on pp. 29 and 30.

No exactness is claimed for this calculation. Its purpose is simply to convey to the reader's mind the general order of magnitude of the work required of each of the four propellers in Fig. 7. The diameter of each blade is 15 feet, and when each of the four shafts carries a four-bladed propeller, the load per blade will work out at $\frac{7800}{4} = 1950$ thrust h.p.

But these ships are now driven at more like 26 knots, and the load per blade will doubtless often run up to some 2500 thrust h.p., or $4 \times 2500 = 10{,}000$ thrust h.p. per propeller.

We have seen that Admiral Oram, Sir William White, and others have, on certain occasions, appeared to incline to the opinion that any inferiority in the efficiency of high-speed, as compared with low-speed, propellers is due to their relative novelty, and that it merely requires the expenditure upon them of an amount of study and experimentation comparable with that which has been applied to the low-speed propeller, to arrive at designs with equally good efficiencies. From the views as expressed by Prof. Biles ("The Steam Turbine as applied to Marine Purposes," Chas. Griffin & Co., London, 1906), and by Mr. H. A. Mavor and others, it would appear that they recognize fundamental reasons for an inherent inferiority of the high-speed propeller as regards efficiency. Thus Mr. Mavor states: "The use of the steam turbine has given rise to new difficulties with the screw propeller. These two are subject to the same fundamental principles, and, if worked in the same fluid, they would be, to a large extent, convertible in their function. A water turbine and a centrifugal pump are essentially similar, and of about equal efficiency at approximately equal speeds of revolution. The great difference in density of the fluid operating the steam turbine and the fluid operated upon by the propeller involves a very different blade velocity, and renders the combination of the two elements at equal speeds of rotation essentially inefficient. . . . It is well known that with marine propellers high efficiency is associated with low speeds. . . . Within the limits of practice the efficiency of the steam turbine is increased by increased speed of revolution, while the efficiency of the propeller is decreased by a corresponding change." Nevertheless, Mr. Mavor does not now claim any *great* superiority for the low-speed propeller as regards efficiency, and he agrees that the size of the propeller is often "fixed by other conditions than the means of propulsion." He

states that "claims for improved propeller efficiency, or even improved turbine efficiency, which had been made in the early stages of the suggestion for introducing electricity for the propulsion of ships could not be realized in practice."

From a contribution to the discussion of a paper read by Mr. Mavor on February 18, 1908, before the Institute of Engineers and Shipbuilders in Scotland, Prof. Biles may be quoted as follows: "The first point to consider was, was it desirable to have any kind of alteration of speed between the generator and the propeller? At present they were directly connected. It was not necessary for electrical engineers to decide the question of whether some transmission system should be introduced, because there was no doubt that the loss of efficiency existed in direct-connected arrangements, where the propellers ran at a very high speed." Prof. Biles alluded to "another book, . . . where it was clearly shown from Taylor's experiments that high efficiency of propeller lay generally with large diameters and low revolutions, and low efficiency with high revolutions and small diameters. . . . This tendency was accentuated at sea, when the resistance of the ship was increased and the speed reduced. In this condition the large diameter of propeller held up to its work still better than the small one. Hence, from a naval architect's point of view of obtaining high efficiency at sea, as well as on trial, it was desirable to have large, slow-running propellers." In Prof. Biles' treatise on "The Marine Steam Turbine," it is shown in chap. iv., entitled, "Screw Propellers in Turbine Vessels," that if the steam turbine is direct-connected to the propeller, it is always necessary to compromise in the selection of the speed at which they shall both run, the most economical speed always being much lower than would be selected were the economy of the steam turbine the sole consideration, and much higher than would be selected were it simply a question of the efficiency of the screw propeller.

In his Presidential address, in November, 1910, at the Junior Institution of Engineers, from which we have already quoted on p. 28, Admiral Oram described as follows the effects of the introduction of steam turbines on the method of procedure in designing the machinery for a warship:—

"An extraordinary alteration in the usual conditions of design had followed from the substitution of turbines for reciprocating

engines. In the latter, the number of revolutions per minute was determined by the engine arrangements only, and was settled from experience with previous examples, having regard to their size and the allowable piston speeds and considerations of inertia. The revolutions having been decided on, the speed of ship gave the pitch, allowing for a slip determined from experience, and hence followed the suitable diameter of propeller. Revolutions of turbines, however, were settled on radically different lines, as, if the engineer first decided on the revolutions he would like to adopt, and proceeded as before, he would generally arrive at a propeller which was quite unsuitable. Considering the turbines alone, there was practically no limit to the number of revolutions which could be adopted even with large powers, and it was necessary to proceed to the propeller to determine the revolutions of shaft which were permissible. The area and diameter of the propeller had therefore to be decided from the estimated thrust, and knowing from experience the practical limit to the thrust per square inch of projected propeller area (about 12 lbs.), the area was fixed, and the diameter was thus obtained. The narrow limits admissible as regards ratio of pitch to diameter for an efficient screw, then gave the pitch, from which, and the speed of the ship, the maximum revolutions were determined. These revolutions were made as high as practical limitations would allow."

This description involves a clear admission of the importance of low propeller speed. At a later stage in his address Admiral Oram said—

"No doubt a large-diameter propeller assisted the manœuvring power of a ship, but the diameter was frequently limited by hull considerations; and electrically-driven ships, with the same number of propellers, driven slower, would in some cases be limited to practically the same dimensions as in direct-driven installations."

On page 222 of No. 2 of vol. 30 of the *Proc. American Inst. Elec. Engrs.* (February, 1911), Mr. W. L. R. Emmet states: "The speed of revolution of shafts must be suited to the power delivered, and to the speed of the vessel, if good efficiency is to be obtained. There is much difference of opinion concerning the possible relations of propeller speed and efficiency. The following table gives an estimate of propulsive coefficients of a large battleship. These

figures are ascertained by comparison of several sources of information, and should be considered only as a rough approximation."

Revolutions per minute.	Propulsive coefficients (two propellers).
100	0·56
150	0·53
200	0·51
250	0·49
300	0·47

In an article in the *Times* "Engineering Supplement" for July 29, 1908, entitled, "Steam Trials of the American Scout *Salem*," the writer states: "Every means was taken to secure efficient propellers. For the *Salem*, four competitive designs for propellers are said to have been obtained, including one from this country and another from Germany. Experimental runs were made on measured distances with these rival propellers and great variations in efficiency are said to have been demonstrated. The propellers finally adopted were designed by the builders, and are said to have given *from* 16 *to* 25 *per cent. greater efficiency* than the others tried. On the basis of information furnished by the Fore River Company, it appears that at the highest speed attained by the *Salem*, the proportion of effective h.p. to shaft h.p. was about 60 to 100."

There emerges from the varied opinions which have been adduced in this chapter the certain conclusion that the achievement of high efficiency in propellers is still a matter for experimentation, and that even the best-informed naval architects and marine engineers are still unable to state the efficiency in any given case with any degree of precision. It has been stated by Mr. Mavor,[1] and it is evident from the many views I have quoted in this chapter, that "it is rarely known what is the actual thrust imparted by the propeller to the ship." The shaft h.p. may be determined with sufficient exactness in any case, but the thrust h.p. remains a quantity regarding which the estimates of engineers are greatly at variance.

In my own opinion, there remains no room for doubt that on the hypothesis of equal skill in design and construction, the lower the speed of revolution of the propeller (within usual limits), the higher will

[1] *The Electrician*, June 10, 1910, p. 16.

be its efficiency. This is an inherent property. The difference may be minimized, but it can hardly be expected that it will be eliminated. When in particular cases this conclusion appears not to hold, there is reason to conclude that the conditions attending the design and construction have been more favourable in the case of the high-speed propeller. Consequently in any comparisons worked out in this treatise, a certain, though small, difference in the efficiency will be made in favour of the low-speed propeller.

Durtnall has proposed a radical departure in propeller construction. This is described on p. 151 of Chapter XV., and is illustrated in Fig. 40, on p. 153.

CHAPTER VII

MECHANICAL SPEED-REDUCTION GEARING FOR STEAM TURBINES

WE have seen in the last chapter that when the ship's engines are direct-connected to the propellers, the propeller efficiency will, for a given speed of the ship, be higher the lower the speed selected for the engines. But for high-speed ships there is required a large engine capacity per ton of weight of ship, and there is ultimately reached a point where it is no longer in the interests of commercial economy to devote chief attention to propeller efficiency. Indeed, we have seen that while there still remains a difference in favour of the low-speed propellers, this difference is by no means great. Consequently it does not justify employing enormously heavy low-speed engines and thus increasing the total weight of the ship and decreasing its cargo- or passenger-carrying capacity. As a matter of fact, in boats of the capacity of the *Mauretania* and *Lusitania*, the size of low-speed piston engines capable of providing a speed of 25 to 26 knots is so great that it would be very difficult to fit such large engines. Consequently, even at the cost of some sacrifice in propeller efficiency, it is in the interests of commercial economy to resort to engines of higher speed and smaller size. The preferable speed for steam turbines is several times greater than that of piston engines of equal capacity. It is an inherent attribute of steam turbines that the higher the peripheral speed of the rotor (at any rate within the limits of the mechanical strength of materials at present available) the greater is the attainable efficiency. Were it not for the consideration of propeller efficiency, a 10,000-h.p. steam turbine would be designed for a speed of the order of from 600 to 1200 r.p.m. This is the practice with land

turbines. For instance, the new electricity supply station at Dunstan, near Newcastle, contains three 10,000-h.p. 1200-r.p.m. turbines. But at a speed of 25 knots, the *Mauretania's* turbines are driven at a speed of only about 190 r.p.m., and the turbines are not only much larger, heavier, and more expensive than high-speed land turbines of the same capacity, but they are less economical of steam. This sacrifice is made in the interests of obtaining some small approach to reasonably-high propeller efficiency. Even at this speed (190 r.p.m.) the propellers probably have some 10 per cent. lower efficiency than could be obtained with propellers of the same output and designed for a speed of, say, 120 r.p.m. for the same vessel-speed of 25 knots.

Let us examine this question further. The weight of the four main turbines (*i.e.* excluding the reversing turbines) of the *Mauretania* runs to some 1200 tons. They are capable of a continuous output of some 65,000 h.p. Thus the output reduces to some 54 h.p. per ton of weight of the main turbines. Steam turbines of the same capacity, but driven at a speed of 600 r.p.m. instead of 190 r.p.m., would have had a weight of only some 600 tons. This difference of some 600 tons in the weight of the turbines does not, in itself, constitute any serious objection, for, taking the condensing plant, steam piping, reversing turbines, boilers, propeller shafts, and propellers, into account, the total weight of machinery incident to propulsion amounts to some 8000 tons, of which 600 tons is not a large percentage. But even without resorting to the use of superheated steam, the steam consumption of the 190 r.p.m. turbines is some 5 per cent. to 10 per cent. greater than that of equivalent 600 r.p.m. turbines.

The boiler plant and condenser plant on the *Mauretania* account for some 5000 tons, and with, say, 7 per cent. less steam consumption, the weight of this plant would be reduced by some 5 per cent., or to, say—

$$(0{\cdot}95 \times 5000 =)\ 4750 \text{ tons.}$$

The *Mauretania* burns some 5000 tons[1] of coal in crossing the Atlantic. With 7 per cent. decrease in steam consumption the amount of coal burned would be reduced to some—

$$(0{\cdot}93 \times 5000 =)\ 4650 \text{ tons.}$$

[1] The coal consumption is now probably a good deal less, but for the purposes of the present explanations, the round figure of 5000 tons suffices.

A rough estimate of the decrease in weight is thus—

Saving in weight of turbines	600 tons
" " " " boiler and condenser plant	250 "
" " " " coal	350 "
Total saving in weight	1200 "

But of what use is it to show that if we could employ 600 r.p.m. turbines in place of 190 r.p.m. turbines we could effect a reduction in weight of machinery of (600 + 250 =) 850 tons, and a reduction in weight of coal of 350 tons, or a *total* reduction in weight of (850 + 350 =) 1200 tons? Why should any interest attach to a knowledge of this fact, since suitable and efficient propellers of this capacity cannot be designed for a speed of 600 r.p.m.? The reason why this calculation is of interest, is that it has been maintained that instead of driving inefficiently-high-speed propellers direct from inefficiently-low-speed steam turbines, speed-change transmission devices should be interposed between efficiently-high-speed turbines and efficiently-low-speed propellers. The transmission devices which have been proposed may be grouped in two classes: I. Mechanical; and II. Electrical.

Let us assume that, by means of such devices, we are able, in such a case as the *Mauretania*, to employ 600-r.p.m. steam turbines and 100-r.p.m. propellers; that the decrease in the steam consumption of the turbines is 7 per cent., and that the improvement in propeller efficiency, as compared with the 190-r.p.m. propellers now actually employed on the *Mauretania*, amounts to 7 per cent. The saving in weight of machinery due to 7 per cent. decrease in steam consumption of high-speed as compared with low-speed steam turbines was taken into account in the preceding calculations, and was taken as amounting to a total of 1200 tons. It will be sufficiently exact to now double the savings in weight of boiler and condenser plant and in weight of coal, since we have the further 7 per cent. decrease in propeller losses. Thus we have—

PRELIMINARY ESTIMATE.

Saving in weight in turbines (1200 − 600 =).	600 tons
" " of boiler and condenser plant (5000 − 4500 =)	500 "
" " of coal (5000 − 4300)	700 "
Total saving in weight	1800 "

The output now required for a speed of 25 knots is—

$$0{\cdot}93 \times 65{,}000 = 60{,}500 \text{ shaft h.p.}$$

This lesser required output has not been taken into account in estimating the saving in weight of the steam turbines. It may be roughly estimated that their weight will be 570 tons instead of 600 tons. Thus we have—

CORRECTED ESTIMATE.

Saving in weight of turbines (1200 − 570 =)	630	tons
„ „ boiler and condenser plant	500	„
„ „ coal	700	„
Total saving in weight	1830	„

This is made up of (roughly) 1100 tons of machinery and (roughly) 700 tons of coal, or a total of (roughly) 1800 tons.

It is not for one moment asserted that the assumptions underlying these calculations are the most appropriate, or even that the weights are more than roughly correct; the purpose of the comparison is simply to explain the nature of the proposals which have been made in advocacy of the use of intermediate transmission gearing.

The margin which we have to apply to this purpose is represented by the weight and cost of the 1100 tons of machinery and the outlay for the 700 tons of coal saved on each journey. It will be convenient in advance to work out the tons of coal saved for each per cent. improvement in economy. The aggregate improvement in economy is—

In the steam turbines	7	per cent.
In the propellers	7	„
Aggregate	14	„

Thus we have a saving of ($\frac{700}{14}$ =) 50 tons of coal for each per cent. increase in overall efficiency.

The most obvious suggestion is, that mechanical speed-reduction gearing should be interposed. Until recently it would have been deemed out of the question to transmit thousands of h.p. through mechanical speed-reduction gearing, at any rate, with any satisfactory

FIG. 8.—A 6000 h.p. Melville-Macalpine Speed-Reduction Gear.

[*To face p.* 40.

efficiency. But with gradually increasing experience in design, with command over improved quality of steel, and with the development of accurate special machinery for gear-cutting, the condition of affairs has gradually altered, and the problem no longer presents insuperable difficulties. The improved results are accomplished chiefly by intelligent designing and by accurate manufacture from high-grade material and with special and expensive machinery. No single firm of gear manufacturers can claim any exclusive ability in this direction. Nevertheless, the Westinghouse Company has been amongst the first to make progress in this field. Mr. George Westinghouse has published a pamphlet entitled, "Broadening the Field of the Marine Steam Turbine: The Problem and its Solution." The pamphlet is devoted to a description of the Melville-Macalpine Reduction Gear, which is stated to make possible "any reasonable speed ratio between the turbine shaft and the propeller shaft."

In Fig. 8 is shown a perspective view of the Westinghouse gear with the casing partly broken away. The illustration relates to the first large gear which has been made to the Melville-Macalpine designs. It is a double helical spur gear, designed with involute teeth, and with capacity for transmitting 6000 h.p. at a pinion-speed of 1500 r.p.m. The pinions have 35 teeth and the spur wheels have 176 teeth. The 176th tooth constitutes a hunting cog and equalizes the wear. The pitch-circle diameters are 14 ins. and 70 ins. respectively. The ratio of reduction is thus practically 5 to 1, consequently the power is delivered from the gear at a speed of only 300 r.p.m. Messrs. Krupp, of Essen, supplied the forgings for the gears. The teeth were cut by Messrs. Schuckardt and Schütte, of Chemnitz. The complete machine was built by the Westinghouse Machine Company at Pittsburg.

The pitch-line speed is 5500 ft. per minute (28·0 meters per second), and the design is based on a limiting pressure of 450 lbs. per inch of tooth contact. To keep within this value required the broad teeth seen in the illustration. Provision is made for the liberal use of lubricating and cooling oil. The gear weighs 27 tons. An excellent description of this gear, accompanied by a number of illustrations, has been published at page 377 of vol. 88 (Sept. 17, 1909) of *Engineering*. In the article in *Engineering* (and in Mr.

Westinghouse's pamphlet entitled, "Broadening the Field of the Marine Steam Turbine") it is pointed out that at a rating of 6000 h.p., the gear would be "of the correct power for the *Dreadnought*, and, applied to her, would save fully 50 per cent. of the weight of her turbines, besides reducing boiler weights, since both turbines and propellers would now be of considerably enhanced efficiency." The statement continues: "Increasing, by the law of comparison for similar machines, the dimensions and power of the present design, from 6000 h.p., a size is obtained suitable for the *Mauretania* with three large screws of the same total power as the present four-screw ship. Here again, the weight of the turbines would, it is claimed, be halved, as also the engine-room length. The boilers also, as in the *Dreadnought*, would, it is considered, be materially reduced. In Fig. 9, the lowest view represents the *Mauretania* thus modified, as compared with the existing arrangement shown in the two upper of the three views."

On p. 247 of vol. 179 (issued Feb., 1910) of the *Proc. Inst. Civil Engineers*, Rear-Admiral Melville, in describing the tests of this gear, writes—

"A full-power test of 6500 h.p. was carried out for a period of 40 hours from 2.30 P.M. on Oct. 16, 1909, till 6.30 A.M. on Oct. 18, 1909. At the close of this test the gear was found to be in excellent condition and without any signs of wear. This established without question the fact that gearing could be used to transmit such large powers continuously at high speed. Continuous brake readings were taken during this test, and other sets of brake tests were made direct on the turbine, so that the turbine conditions were identical in the two sets of cases, from which it was determined that the gear showed an efficiency of 98·5 per cent. This was checked in another way, by measuring the increase in temperature of the oil used in lubricating the gear, and (in a very rough way indeed) by simply feeling the teeth at the end of the run, when they were found to be cold. . . . The weight of the gear used in the test, complete, including bedplate, framing, casing, etc., was 61,000 lbs. (27 tons). For the 6500 h.p. of the test, this gave 9·4 lbs. per h.p. There was every reason to believe, however, that with a slight increase of some parts of the transmission, the gear, as it stood, would be good for 10,000 h.p., in which case the weight would be 6·2 lbs. per h.p."

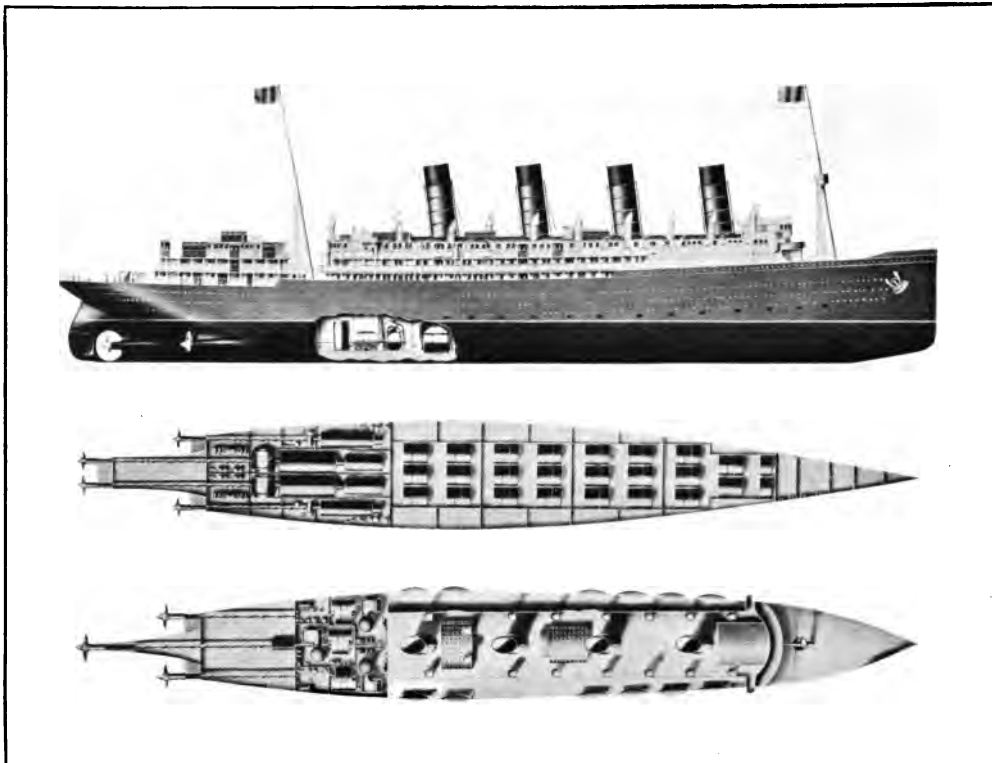


FIG. 9.—The *Mauretania*, as at present, with 4 Screws and Direct Drive, and an alternative design, with 3 Screws and Melville-Macalpine Drive.

[*To face p.* 42.

At p. 52 of Mr. Westinghouse's pamphlet (entitled, "Broadening the Field of the Marine Steam Turbine"), Mr. Macalpine states, in the concluding paragraphs of a letter dated Nov. 29, 1899: "Lastly, we have practically no wear, as the tool-marks still show prominently in the teeth. This is partly due to copious lubrication and partly to the well-distributed tooth-contact. Hence the life of the pinion will be long, possibly as long as that of the ship. The perfect action of the whole gear is shown by the high efficiency attained, which, at 6000 h.p., is over 98·5 per cent. and probably as high as 99 per cent. By using a steel of high elastic limit but still ductile, we have no doubt we could with perfect safety raise the power transmitted by the present machine, which weighs 61,000 lbs., to 10,000 h.p. at 1500 r.p.m.; and there is no indication that this is the limit of peripheral speed at which these gears can be run."

At p. 8 of the introduction (dated Oct. 15, 1909) to the pamphlet to which allusion has been made above, Mr. Westinghouse points out that: "In the case of a battleship or a cruiser, maximum speed is only an emergency condition. The normal cruising speed is only about 60 per cent. of the maximum speed, and requires perhaps less than 25 per cent. of the maximum power. It is at the cruising speed that turbine-propelled naval vessels have shown to disadvantage as compared with vessels propelled by the best types of reciprocating engines. By reason of the more liberal blading that is possible in a high-speed turbine, its economic performance is less sensitive to departures from maximum rotative speed, than is that of the low-speed turbine. Furthermore, as the entire expansion of the steam takes place in a single turbine, the total power may be distributed conveniently among three entirely independent units, driving one central and two wing propellers. The central unit alone will suffice for ordinary cruising speeds, and can be operated always at somewhere near its most economical conditions of working. . . . The United States Government has lately awarded contracts for two new battleships to be equipped with steam turbines. These battleships are to have a speed of 20½ knots, which will require, in round numbers, 28,000 shaft h.p. With 55 per cent. propeller efficiency, the effective propelling power will be about 15,400 h.p. With the 65 per cent. propeller efficiency that is easily possible with the reduction-gear and a propeller at a lower speed of revolution, this

same propelling power would require less than 24,000 h.p. on the shaft. The average steam consumption guaranteed at full power is about 14½ lbs.[1] per shaft h.p.-hr. With the better steam economy of the high-speed turbine, the boiler capacity required would be reduced fully one-third. With the same bunker capacity, the radius of action would be enormously increased, which is an advantage of incalculable value. If the same boiler equipment as is now proposed were maintained, there would still be a saving in weight of over 250 tons, or approximately one-eighth of the total penalty-weight of the machinery in each ship, resulting solely from the substitution of the high-speed turbine and reduction-gear for the more cumbersome, slow-speed, direct-connected machine. At the same time, by reason of the well-known overload capacity of a liberally-proportioned turbine, there would be available a surplus power of about 50 per cent., which should make possible an emergency speed of nearly three knots in excess of that called for in the specifications. Furthermore, the three independent shafts, each with its own self-

[1] In an additional note, dated Jan., 1910, and included in his pamphlet, Mr. Westinghouse states that: "The figure of 14·5 lbs. per shaft h.p.-hr. was assumed for the reason that the latest tenders made to the United States Government for battleships to be propelled by turbines made according to plans supplied by the owners of Mr. Parsons' U.S. patents, specified a steam consumption not exceeding 14·7 lbs. per shaft h.p.-hr., and it naturally would not be expected that this water-rate could be greatly bettered. However, we have since been favoured with specific information in the able and comprehensive Presidential address on the 'Propelling Machinery of Warships,' delivered before the Junior Institution of Engineers on Nov. 16, 1909, by Vice-Admiral H. J. Oram, Engineer-in-Chief of the Fleet. Admiral Oram's sound engineering judgment, coupled with unusual opportunities for following the progress of the marine steam turbine in the Royal Navy, are such that I fully accept his statements, and record my acknowledgment of the value of his address by making a brief quotation from the section in which he deals with the efficiency of the turbine." Mr. Westinghouse then gives quotations which contain the data of actual steam consumptions of some turbine-engined ships. For the *Dreadnought* "the consumption of steam at full power for turbines only" was 13·5 lbs. per shaft h.p.-hr. for an initial pressure of 164 lbs. per sq. in. of gauge pressure. The average steam consumption of the three battleships succeeding this ship was 13·0 lbs. per shaft h.p.-hr., with an average gauge pressure of 174 lbs. per sq. in. on the high-pressure turbine. Finally, for the turbine engines of the *Indomitable* class, the average steam consumption at full power, for turbines only, was 12·0 lbs. per shaft h.p.-hr., with the average gauge pressure of 123 lbs. per sq. in. at the high-pressure turbine. I do not consider that these improved results as regards steam consumption in any way affect Mr. Westinghouse's case, for they are simply indicative of progress in the improvement of the steam turbine, and do not affect the question of the RELATIVE consumptions of high-speed and low-speed steam turbines. The former are inherently more efficient, and are also smaller and cheaper.

Fig. 10.—A 7500 h.p. Westinghouse Marine Steam Turbine with the Melville-Macalpine Speed-Reduction Gear.

[*To face p.* **44.**

contained turbines for going ahead and astern, would give the excellent manœuvring qualities which are *admittedly lacking in vessels fitted with the present conventional turbine equipment.*"

Fig. 10, taken by the kind permission of Mr. Westinghouse from a 1910 publication entitled, "The Westinghouse Marine Steam Turbine, with Melville and Macalpine Reduction Gear," is a general perspective view of a 7500-h.p. Westinghouse marine steam turbine for driving through a Melville-Macalpine gear. It will be seen that all pipe connections are made to the lower half of the casing. The two controlling valves, one for the ahead and one for the astern turbine, and the electro-pneumatic and hand-operating gear may be seen at the left of the exhaust opening.

Fig. 11 (on the Plate facing p. 47) shows a proposed arrangement of Westinghouse marine steam turbines with speed-reduction gear as proposed for U.S.S. *Baltimore.* The entire equipment is shown as if installed in one of the two engine-rooms occupied by the reciprocating engines with which this vessel was actually fitted.

From the data which I have cited in this chapter, it appears to be conclusive that by the Melville-Macalpine gear a steady load of 6500 h.p. can readily be transmitted for indefinite periods through gearing machinery weighing 27 tons, or—

$$\left(\frac{6500}{27}\right) = 240\text{-h.p. per ton.}$$

Since the gearing is of only 98·5 per cent. efficiency—or, to be very conservative, say, 98 per cent., the output from a group of turbines such as would be required to drive the *Mauretania* at a speed of 25 knots will be—

$$\frac{60{,}500}{0{\cdot}98} = 62{,}000 \text{ h.p.}$$

This will require a gearing weight of—

$$\frac{62{,}000}{240} = 260 \text{ tons.}$$

Let us take this as 300 tons, to have a reasonable margin.

The weight of gearing for a ship of the *Mauretania's* displacement and speed would consequently amount to some 300 tons, in place of

a weight of some 1100 tons of machinery, which would be saved. The coal saving would be only some 600 tons, in place of 700 tons, since the latter figure did not allow for the 2 per cent. loss assumed as occurring in the gearing.

Let us take it that such a ship would cross the Atlantic 33 times in a year, thus accomplishing a total of 100,000 miles per annum. Taking the cost of coal at 10*s.* per ton, the cost of machinery at £50 per ton, and the repairs and renewals of machinery at 10 per cent., the total saving per annum works out at—

Saving in fuel $\left(\frac{33 \times 600 \times 10}{20} = \right)$	9,900
„ machinery $(800 \times 50 \times 0{\cdot}10 =)$	4,000
Total annual saving (exclusive of any difference in wages) .	£13,000

Of course, this is a very small annual saving for a ship, the cost of which must have been of the order of a couple of million pounds sterling, but it would appear to be a step in the right direction. The comparison has been exceedingly rough, and has, moreover, been so conservative as regards assumptions, that it is practically certain that the annual saving would be very much greater. My object has simply been to explain a line of reasoning which can be applied in establishing such a comparison. Mr. Westinghouse (p. 7 of "Broadening the Field," etc.) carries out an analogous comparison in a very interesting way. He says: "The turbines of the giant Cunarders, *Mauretania* and *Lusitania*, are supposed to be capable of developing 70,000 shaft h.p. Even the comparatively low speed at which these turbines run is too high for maximum propeller efficiency. It is hardly possible that the propeller efficiency exceeds 55 per cent., which means that the actual effective propelling power is only about 38,500 h.p. At a lower speed of revolution, well within the capabilities of the reduction gear, a propeller could be made that would have an efficiency of not less than 65 per cent. With this improved efficiency, the shaft h.p. required for the same effective propelling power would be somewhat less than 57,000, a saving of almost 15 per cent. This means that, without sacrificing in the smallest degree the remarkable speed of these vessels, the boiler equipment could be reduced about one-seventh, as well as the amount of coal burned on each voyage. This would not only result in a very

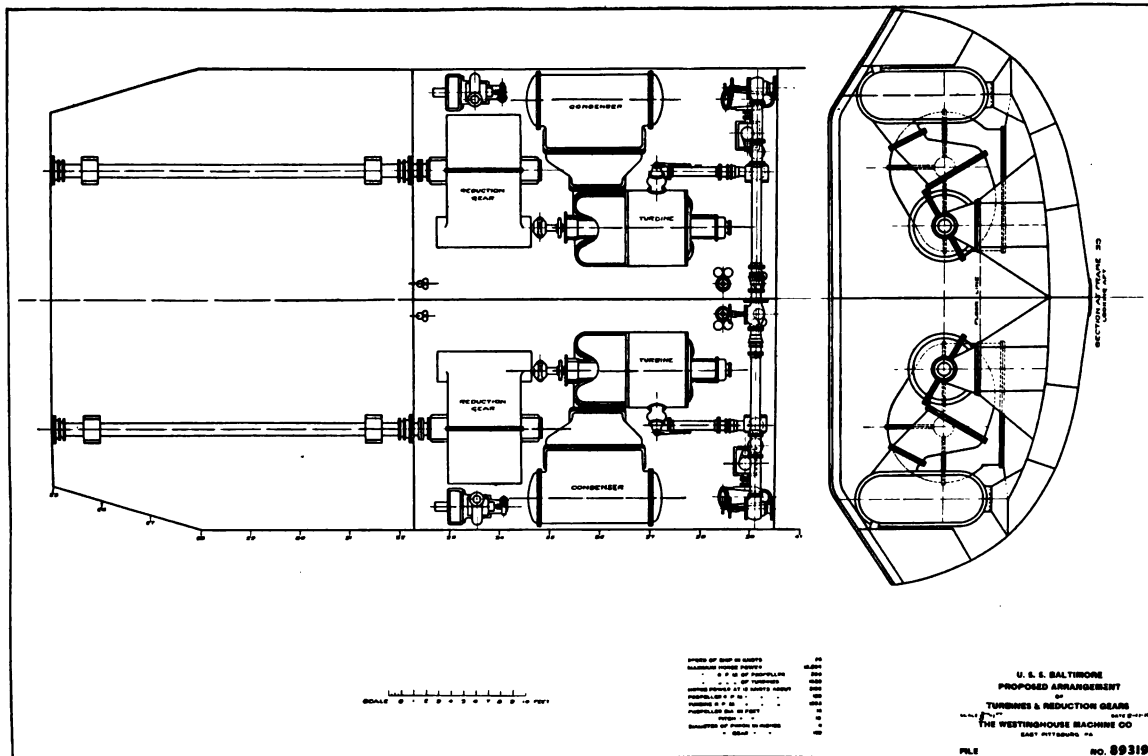


FIG. 11.—Arrangement of Westinghouse Marine Steam Turbines with Melville and Macalpine Reduction Gear, as proposed for U.S.S. *Baltimore*.

[*To face p.* 46.

marked saving in capital investment and operating expenses, but would add many tons to the cargo-carrying capacity, and add correspondingly to the earning power. But this estimate, large as it is, is still too modest. With the turbine and the propeller direct-connected, so that both revolve at the same speed, not only is it necessary to sacrifice the efficiency of the propeller, but the efficiency of the turbine as well. For equal efficiencies in any two turbines, the number of rows of blades is, roughly speaking, inversely proportional to the squares of the respective peripheral speeds of the rotating elements. The peripheral speed of the rotating elements in the turbines of the *Mauretania* and *Lusitania* is only one-third of the speed common in large turbines used on land. This would mean that to obtain the efficiencies common to the latter the former would require approximately nine times as many rows of blades, which would make a machine of prohibitive length. To maintain the same speed of revolution, and increase the peripheral speed of the turbines of these vessels to the point common in land practice, the rotors would have to be nearly forty feet in diameter, which is manifestly beyond the shadow of possibility. From the best information obtainable, it is believed that the steam consumption of the turbines of the *Mauretania* and *Lusitania* cannot be less than 14·5 lbs. per shaft h.p. per hour, while it has been demonstrated beyond question that for turbines of similar capacity, operating at speeds which the reduction gear makes possible for marine service, the steam consumption does not exceed 11 lbs. per shaft h.p. per hour. This means that the boiler capacity could be further reduced from the first estimate of 60,000 h.p. to about 45,000 h.p., and the over-all efficiency of the installation would be sufficiently improved to result in a reduction of over 35 per cent. in the coal consumption. It is unofficially reported that the coal consumption of these vessels is about 4700 tons per voyage. Reckoning the cost of the coal at $3.25 per ton, the saving in coal alone would be $5300 per voyage, to say nothing of the smaller cost for wages and sustenance for the lesser number of stokers that would be required. The increased cargo capacity, resulting not only from a reduction of over 1600 tons in the coal required to be carried on each voyage, but also from the greatly reduced weight of the equipment and the space necessary for it, is an asset the value of which it is difficult to overestimate. . . . The *Mauretania* and

Lusitania have two high-pressure and two low-pressure turbines, and two reversing turbines, working on four shafts. According to the best information obtainable, the high-pressure turbines have each 128 double rows of blades, and the low-pressure turbines 60 double rows each. The total length of the blading, exclusive of the relatively small amount in the reversing turbines, is about 115 miles, and the total surface area of the blades is considerably more than three-quarters of an acre, or equal to the sail area of a large ship. By using the reduction gear, the same total propulsive power could be installed in three turbines. There is nothing problematical about this statement, as turbines developing the requisite power, and of the same general design as would, in connection with the reduction gear, be suited to marine work, have been operating successfully for a long time, and their power and economy are now matters of authentic record. Each turbine would have only 51 double rows of blades, a total in the three turbines of 153, or only 25 in excess of the number of rows in one of the high-pressure turbines alone in the present installations on board the Cunard flyers. The total length of the blading in the three high-speed turbines would be less than 6 per cent. of that in the low-speed turbines. Each shaft would be driven by a complete and independent self-contained turbine, and each shaft would have its own reversing turbine, so that the entire screw equipment would be available for backing, instead of only one half of it, as is the case in the present arrangement."

The arrangement proposed by Mr. Westinghouse is that already illustrated by the lowest plan view in Fig. 9, on the Plate facing p. 42.

In the summer of 1911, a set of Westinghouse reduction gearing was installed on the United States collier *Neptune*. It is claimed that both the weight of the machinery and the steam consumption will be reduced much below the values corresponding to direct drive between turbine and propeller.

In March, 1910, Mr. Parsons read a paper before the Institution of Naval Architects, entitled, "The Application of the Marine Steam Turbine and Mechanical Gearing to Merchant Ships." In the paper it was pointed out that while direct drive by steam turbines is appropriate and economical for high-speed ships, no promising scheme had been evolved, having for its object the modification of the turbine or

propeller for vessels of 12 knots sea-speed and under. This would be accomplished if the steam turbine could be made efficient at the low speeds corresponding to efficient propellers, or if efficient propellers could be designed for the high speeds corresponding to conditions of best efficiency for steam turbines. Since there was no likelihood of much success in either of these directions, Parsons concluded that the most satisfactory solution for slow-speed vessels would be by means of gearing, provided the energy loss in the gearing, the first cost of the gearing, and the cost of its maintenance, should not prove to be too great. These considerations have led Parsons to investigate the practicability of employing speed-reduction gearing for ship propulsion, so as to be able to instal high-speed, and consequently economical and light, steam turbines, and low-speed, and consequently more efficient, propellers. He states that gears that had recently been cut by special machinery by the Power Plant Co. worked with very little noise. He also states that a recent experimental set of gearing, cut by Messrs. D. Brown of Huddersfield, with a speed reduction from 2000 to 400 r.p.m., was tested when transmitting 300 h.p., and was found to give a total loss in the gear case, including friction of gear and bearings, of only 1·5 per cent. In the year 1909 Parsons determined to make tests with turbines mechanically geared to the propeller shaft of the *Vespasian*, a typical slow-speed cargo vessel. The *Vespasian* has the following dimensions:—

Length on load water-line	275 ft.
Breadth moulded	38 ft. 9 ins.
Depth moulded.	21 ft. 2 ins.
Mean loaded draught.	19 ft. 8 ins.
Displacement	4350 tons

Originally the *Vespasian's* propulsive machinery consisted of a triple-expansion, surface-condensing engine, with cylinder diameters of 22·5 ins., 35 ins., and 59 ins. The stroke was 42 ins. Before taking out this original machinery, tests were made under service conditions. For this purpose it was arranged for the vessel to take a cargo of coal from the Tyne to Malta. Throughout the trip the consumption of coal and water was measured. After her return the engine was taken out, but the original boilers, propeller, shafting, and thrust blocks were retained. The new propelling machinery

consisted of two steam turbines. The steam was taken at high pressure through one of these turbines; and after passing through this turbine, the steam, now at low pressure, was taken to the other turbine, which was designed as a low-pressure turbine. The high-pressure turbine was installed on the starboard side, and the low-pressure turbine on the port side. Each turbine drove the pinion shaft of a speed-reduction gear, through a flexible coupling. The two driven pinions both geared into a single gear wheel, which drove the propeller shaft. The exhaust casing of the low-pressure turbine contained a reversing turbine. The gear wheel was of cast iron, with two forged-steel rings shrunk on. The gear wheel had 398 double-helical teeth, and a pitch-circle diameter of 8 ft. 3·5 ins.

The pinion shafts were of chrome nickel steel, with a pitch-circle diameter of 5 ins., and with 20 teeth. The face of the gear wheel had a total width of 24 ins. The gear ratio was thus practically 20 to 1. On March 11, 1910, the vessel was tested on the Tyne with the same load and conditions of draft and displacement as those of the 1909 tests. Amongst the results, the following, relating to water consumption, are of interest:—

Speed of screw.		56 r.p.m.	60 r.p.m.	70 r.p.m.
Water consumption for all purposes in lbs. per hour	1909 tests, with reciprocating engines	9,700	11,700	17,500
	March, 1910, tests with turbine and mechanical gearing	9,400	10,700	14,700
Percentage improvement in economy .		3·0%	8·5%	16·0%

In March, 1911, another paper was read before the Institution of Naval Architects, by the Hon. C. A. Parsons and Mr. R. J. Walker. This paper was entitled, "Twelve Months' Experience with Geared Turbines in the Cargo Steamer *Vespasian.*" It is explained in the paper that since June 9, 1910, the *Vespasian* has been carrying coal from the Tyne to the Continent, returning in water ballast. Between June, 1910, and March, 1911, the vessel made 26 trips to Rotterdam, and 6 trips to Antwerp, and had altogether steamed

20,000 miles. On the occasion of an inspection at the end of this time, it was found that the wear in the teeth had been practically nil, and no slackness in the teeth could be detected. During the course of the year pinions of different materials were tried, and the best results were obtained with pinions made of special carbon steel of some 40 to 45 tons tensile strength, an elastic limit of 22·5 tons, and an elongation of some 20 to 25 per cent.

The water consumption at the average service speed of the *Vespasian* (some 9·3 knots) was some 16 lbs. per shaft h.p. of the main engines. But the authors state that in a new vessel a consumption of some 12·5 to 13 lbs. per shaft h.p. could confidently be expected in a 1000 h.p. installation. They stated that in a large, 4-shaft war-vessel their system would effect a saving in consumption of fully 25 per cent. at a cruising speed equal to one-tenth of the full power, and 30 per cent. at one-fifteenth of the full power. In this statement the comparison is with war-vessels fitted with direct-coupled cruising turbines. Parsons stated in the discussion that his firm had in hand several geared turbines for destroyers. Prof. Föttinger also participated in the discussion of this paper, and expressed the view that the successful use of tooth-gearing could only extend to the limit of some 1000 h.p. per pinion. He admitted that the efficiency of hydraulic gearing was lower, but pointed out that there was no upper limit to the power which could be transmitted by it. Prof. Föttinger estimated the combined efficiency of the tooth-gearing (including the oil pump) at 95 to 96 per cent., and stated that the efficiency of hydraulic gearing was sometimes as high as 90 and 91 per cent.

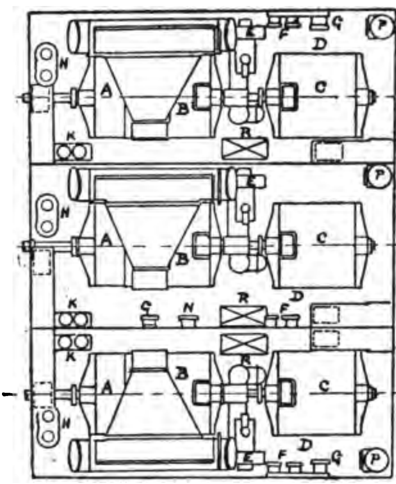
The Föttinger Hydraulic Gear

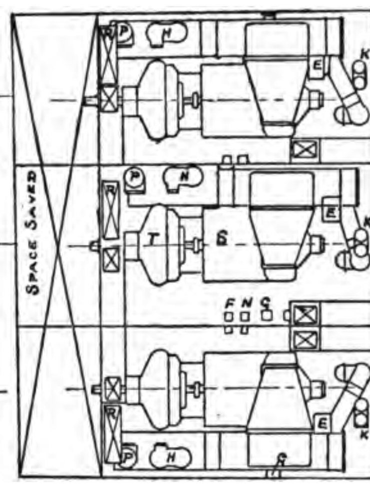
With tooth gearing it is still necessary to provide reversing turbines. The Vulcan Company of Stettin are exploiting the hydraulic gearing devised by Prof. Föttinger, and which permits, not only of securing a wide range of propeller speeds for a constant and high speed of the prime mover, but also permits of reversing the propeller without reversing the prime mover. The efficiency of the Föttinger gear is, under usual conditions of operation, of the order of

rather over 80 per cent. Notwithstanding this somewhat low efficiency, there would appear to be a legitimate field for this system. An excellent description of the Föttinger system, accompanied by 25 illustrations and diagrams, was published at p. 601 of *Engineering* for Nov. 5, 1909 (vol. 88). That article should be consulted for more precise information. In the concluding section of the article, certain interesting comparisons are made. These may be abstracted as follows: For a torpedo destroyer it would be appropriate (where no speed-reduction gear is employed) to instal an 800-r.p.m. steam turbine to develop 3700 effective h.p. The machinery would comprise an astern turbine, and the complete unit would weigh 18·3 tons. But the alternative plan employing the Föttinger gear permits of omitting the astern turbine, and also of building the main turbine for a speed of 2200 r.p.m., this speed being reduced by means of the hydraulic transmission to a propeller speed of only 480 r.p.m. Both the elimination of the astern turbine and the use of a much higher speed for the main turbine so greatly decrease the weight as to more than offset the weight of the Föttinger gear. Moreover, both the turbine and the propeller are of higher efficiency in virtue of the more appropriate speeds at which they are driven, and thus the losses in the hydraulic transmission are at least largely offset. The weight for the complete unit, including the weight of the hydraulic gear, is 14·6 tons, or 20 per cent. less than the 18·3 tons of weight of the turbine machinery in the direct-driven arrangement. But allowing for the increased weight of the slower-speed shafting and propellers, this 20 per cent. saving in the weight of the machinery is decreased to a matter of some 10 per cent.

In Fig. 12 (adapted from an illustration in the article in *Engineering*) is shown a triple-shaft turbine arrangement which is typical of practice on German battleships. Each of the three shafts is equipped with a high-pressure, a low-pressure, and an astern turbine. Each set, with its condenser, is independent, and each set is arranged in a separate water-tight compartment. The ship is provided with 30,000 b.h.p. (*i.e.* 10,000 b.h.p. per shaft). Each shaft runs at 275 r.p.m. For this arrangement, the total weight of the turbines is 592 tons. The alternative arrangement, employing Föttinger gearing to drive the 125-r.p.m. shafting and thus permitting of using not only highly efficient slow-speed propellers but also highly-efficient and

light 720-r.p.m. main-turbines, and moreover also permitting of dispensing with the astern turbines, is illustrated in Fig. 13. This arrangement requires materially less space. The total weight of the turbines, together with the Föttinger transmission machinery, is only 376 tons (or 216 tons less than the weight of the turbines in the usual arrangement shown in Fig. 12). Including shafting and propellers (which, owing to their lower speed, represent a greater





A. Astern Turbine.
B. Low-Pressure Turbine.
C. High " "
D. Engineer's Platform.
E. Circulating Pumps.
F. Oil "
G. Bilge "

H. Wet Air Pumps.
K. Dry Air "
N. Sanitary "
P. Evaporator.
R. Hot Water Tank.
S. Steam Turbine.
T. Transmitter.

Fig. 12.—Plan of Engine-room of Triple-shaft Turbine-driven Battleship.

Fig. 13.—Plan of Engine-room equivalent to that of Fig. 12, but with the substitution of the Föttinger System.

weight in the Föttinger system), the relative weights are stated to be 724 tons for the arrangement shown in Fig. 12, and 600 tons for the alternative arrangement indicated in Fig. 13, employing Föttinger gearing.

Weights and Efficiencies

Throughout all these comparisons the influence of weight and efficiency will be noted. Emmet has published (p. 221 of *Proc.*

American Inst. Elec. Engrs., vol. 30, Feb., 1911) the following table:—

	R.p.m.	Weight in lbs. per h.p.	Thermodynamic efficiency.
12,000 kw. high-speed turbine without generator	1,200	8·5	71 %
Group of Parsons marine turbines designed to give 28,000 h.p. to four propeller shafts	325	42·0	—
North Dakota (Curtis) turbines (two, each 13,000 h.p.)	260	—	56 %

As regards the above figures, Emmet says: "The large differences shown by these figures are incident to speed, a ship turbine being very large, complicated, and expensive, and relatively inefficient, while the high-speed machine is very simple in construction, small and highly efficient." At a later paragraph in the paper, he continues: "The comparison of weights and efficiencies of turbines shown by the figures given above, applies only to certain conditions, and in other cases the comparison might be very different, so that in such a problem every case must be considered on its merits, and its merits cannot be judged until all features of design and operation are worked out in detail."

Further data of weight and cost of machinery are given on pp. 57, 58, 75, 77, 82, 90, 160, and 162.

CHAPTER VIII

ELECTRICAL SPEED REDUCTION GEARING FOR STEAM TURBINES

In the last chapter, descriptions have been given of methods which have been worked out for effecting by mechanical gearing such a change of speed as shall permit of employing high-speed steam turbines and low-speed propellers. It has been claimed that increased economy over the direct drive could be obtained by coupling electricity generators to the steam turbines, and supplying electricity to motors which should drive the propellers. So far as such a proposition is restricted to obtaining the advantages of employing a high-speed prime mover and low-speed propellers, the merits of the proposition (to the extent that the wages items and the annual percentage outlays for repairs and renewals remain the same) may be roughly examined by comparing the relative first-costs and the relative fuel consumptions. Taking such a case as the *Mauretania*, we have seen that the employment of moderately-high speeds for the turbines and the propellers results in decreasing the weight of the turbines by some 600 tons. When electrical speed-reduction gear is used, we are rarely justified in basing our calculations on lower fuel consumption *at maximum speed* of the ship, since usually the gain in operating the turbines and propellers at their efficient speeds is, roughly, about offset by the losses in the generators and motors. This is the state of affairs for ships like the *Mauretania*, which are practically always operated at nearly the maximum speed of which they are capable. We shall see in later chapters that for other types of ships, notably warships, very considerable savings will accompany the electrical proposition, for other reasons which will then be set forth. But even for such a case as the *Mauretania*, the use of

electrical transmission, and the attendant feature of reversible motors, obviates the necessity for reverse turbines. For a ship of the *Mauretania's* class, we may take the weight of the reverse turbines as some 350 tons. Thus the weight of the displaced steam apparatus amounts to some—

$$(600 + 350 =) \ 950 \text{ tons.}$$

The output at 25 knots is a matter of some 65,000 shaft h.p. The electric generators will, however, weigh some 600 tons, and the low-speed electric motors will weigh fully 1200 tons. Thus the 950 tons of steam-turbine machinery is replaced by some—

$$(600 + 1200 =) \ 1800 \text{ tons}$$

of electrical machinery for which the annual outlay for repairs and renewals will be of the order of $\frac{1800}{950}$ times as great.

There should be no need to carry the comparison any further. The precise weights will vary greatly with each particular case and with the electrical system employed, but great as these variations may be, they will not suffice to show any saving by employing the electrical system for such a case. Any noteworthy saving by the electrical system would, for a vessel which practically always runs at its maximum speed, only be obtained were it an established fact that the combined gain in efficiency of propellers and steam turbines is of the order of 15 to 20 per cent.—say some 7·5 to 10 per cent. for each. It would often be well up towards this value were marine engineers to consider it expedient to employ superheated steam, since the efficiency of steam turbines may be very considerably improved by employing superheated steam. This point is discussed in the following chapter.

When dealing with the subject of mechanical gearing in the last chapter, it did not seem desirable, in the example discussed on pp. 38 to 40, to take a greater ratio of speed reduction than 6 to 1. Consequently, since we desired a propeller speed of 100 r.p.m., we fixed the speed of the steam turbine at 600 r.p.m. But with electrical machinery, a greater reduction is equally reliable. Consequently, it is entirely permissible to employ 1200 r.p.m. for the speed of the steam turbines. This brings down the weight (for 65,000 h.p.) to some 450 tons, and increases the saving in weight of

turbine machinery to 1100 tons, as against a weight of some 1600 tons of electrical machinery required to effect the speed reduction. The electrical method thus does away with reverse turbines and also permits of going to the highest preferred speed for the steam turbines without any reference to the ratio of gearing.

As an instance of the weight of the electrical apparatus in a certain case, it is of interest to cite the case of an estimate published by Emmet (*Proc. Am. Inst. Elec. Engrs.*, vol. 30, Feb., 1911, p. 226). It relates to an equipment proposed for a U.S. battleship. The plan consists in installing the machinery in two engine-rooms separated by a water-tight bulkhead. Each engine-room is to contain one 12,000 k.w. generating unit and two 7000 h.p. motors. The estimated weights are as follows:—

Two generating units	300 tons
Four motors	182 „
Switchboards, switches, field rheostats, water-cooled rheostats, accessories	7 „
Cables	8 „
Total weight	497 „

In the course of the discussion on Mr. Emmet's paper, Dr. Charles P. Steinmetz, Chief Engineer of the Consulting Department of the General Electric Co., and Past President of the American Institute of Electrical Engineers, expressed the opinion, "that the introduction of the electric drive would not only give an increase of space, weight, and power efficiency, and thereby an increase of the maximum speed, and an increase of the cruising radius of the ship, *but also a material increase in the promptness of control*, especially under emergency conditions, as exemplified by a great increase of the rapidity of stopping the ship from full speed." On the same occasion Mr. Gano Dunn, President of the American Institute of Electrical Engineers, said: "In the ship of the paper, . . . the turbine and propeller each chooses its own condition of maximum commercial efficiency, high speed for the one and low speed for the other. Independence of direction of rotation, advantages of remote control, and remarkable facility of adjustment, are linked together by an electro-magnetic connection which renders these advantages possible."

In concluding his paper, Mr. Emmet gives an interesting table, reproduced below. He states that the data in the table relate to cases "which have been studied with greater or less degree of thoroughness in order that an idea may be formed concerning the relative desirability of such methods in connection with ships of different kinds." The table is as follows:—

Case.	I.	II.	III.	IV.	V.
Displacement (tons)	19,360	25,000	20,000	10,945	9,900
Shaft horse-power at full speed	6,850	12,500	17,300	2,275	5,500
Ditto at six-tenths speed	—	—	3,400	—	—
Approximate weight of main engines or turbines (tons)	335	411	435	102	—
Weight of corresponding electric drive (tons)	135	237	374	55	133
Full speed (knots)	14	16	20	10·5	14·6
Six-tenths speed (knots)	—	—	12	—	—
Speed of electric drive (r.p.m.)	110	110	148	85	114
Ditto at six-tenths speed (r.p.m.)	—	—	87	—	—
Water rate with electric drive in lbs. per shaft h.p.-hr. (exclusive of auxiliaries)	12·0	11·5	11·5	13·0	12·5
Ditto at six-tenths speed	—	—	12·9	—	—
Steam pressure (gauge pressure in lbs.)	200	200	260	175	181
Saturated or superheated steam	Sat.	Sat.	50° super	Sat.	Sat.
Vacuum (inches)	28·5″	28·5″	28·0″	28·0″	28·0″
Ditto at six-tenths speed	—	—	28·5″	—	—

CHAPTER IX

THE USE OF SUPERHEATED STEAM IN MARINE ENGINES

WHILE rapid advances have been made in the use of superheated steam in land engines, this is not the case at sea. The point is of fundamental importance, as affecting the subject-matter of this treatise, since the feature of employing superheated steam has been a factor of no small importance in the enormous success which has attended the rapid introduction of the steam turbine as a prime mover in land practice. The difficulty associated with cylinder oils at high temperatures has militated against the use of high degrees of superheat in piston engines, but this difficulty is totally absent when steam turbines are used, since no oil then enters the cylinders. When this circumstance became widely recognized, a considerable portion of the prejudice against the use of superheat was gradually overcome. For some time in the earlier days of steam-turbine progress, troubles were encountered owing to the buckling of the turbine blades, and to distortion of the enclosing castings at high temperatures, for the clearances in the earlier turbines were exceedingly small. But experience in the choice of suitable materials led to a considerable measure of success in overcoming these troubles. Furthermore, the impulse type of turbine has now been fairly widely introduced. In this type the importance of small clearances is less acute. But by far the greater numbers of marine steam turbines are still of the reaction (Parsons) type, the economy of which is very dependent upon the use of the smallest practicable clearances. Moreover, as we have seen, in order to obtain reasonably good results as regards propeller efficiencies, the speeds employed in marine turbines are very much lower than are employed in land turbines of equal

capacities. This leads to ship turbines of relatively very large diameters, and it is consequently much more difficult to make the cases sufficiently rigid to withstand slight distortion with great temperature variations. Owing largely to the influence of these considerations, the prejudices against the use of superheat in marine turbines are still far from being overcome. With the imminent introduction either of mechanical or electrical means for speed reduction and the consequent employment of turbine speeds such as are used on land, the chief reasons for objecting to the use of high superheat would appear to no longer hold. The high-speed turbine is of relatively small diameter, and its casing is thus more rigid. If of the impulse type, the clearances are greater. Consequently there is justification in projects where the turbine speed is high, for taking advantage of the materially lower steam-consumptions which, in land turbines, have been widely and conclusively demonstrated to be entirely practicable. The feasibility of various projected schemes for the electric propulsion of ships is dependent in no small measure on this point. In a letter by Mr. Rosenthal, managing director of Messrs. Babcock and Wilcox, published in the *Times* "Engineering Supplement" for Sept. 28, 1910, it is asserted that there is a decrease of 1 per cent. in coal consumption for every 3·3° Cent. (6° Fahr.) of superheat. Mr. Rosenthal states that, "in a paper read at the Engineering Conference in 1907, where the actual results of the tests made by the Admiralty on H.M.S. *Britannia* were given, the gain in coal economy due to a superheat at the boilers of 93° Fahr. (51·5° Cent.) was shown to be 14·5 per cent., the gain in steam consumption of the engines being 13·5 per cent.; in other words, there was a gain of 1 per cent. in coal consumption for every 6° Fahr. (3·3° Cent.) of superheat, and not for every 25° Fahr. (14° Cent.) as stated by Mr. Parsons. The reason that the percentage of gain in steam economy is actually greater than the percentage gain in coal consumption is due to the fact that with properly designed superheaters and boilers a more effective utilization of the heat produced from the fuel is actually obtainable, owing to the retarding action on the gases of combustion, and this was proved on the trials of the *Britannia*. In that ship the boilers are Babcock and Wilcox, some of which are fitted with superheaters and some without, but throughout the trials the boilers which were fitted with superheaters had a

lower uptake temperature than those not fitted with superheaters, thus showing that a better utilization of the heat was obtained when superheaters were attached to the boilers. In these boilers the arrangement was such that there was no increase in either weight or space required to fit the superheaters; therefore there is nothing to set against the gain obtained, so far as the boiler installation is concerned."

The above letter doubtless gives a more optimistic view of the advantages of superheat than is usually held in disinterested quarters. Nevertheless, on the other hand, it is hard to refrain from ascribing a certain amount of the opposition to the use of superheat in marine turbines to the circumstance that 4,500,000 h.p. of the steam turbines as yet fitted on ships are of the reaction type, *i.e.* they are of the type which is usually regarded as least immune from the troubles inherent to small clearances. The advantages of the impulse type, so far as relates to the practicability of large clearances are gradually coming to be more widely recognized, and with the increasing use of the impulse type, the employment of superheat will probably become more usual, especially in the event of the introduction of higher-speed turbines for marine work.

However, it would be well, pending the accumulation of further data, to estimate on a rather moderate percentage saving, say, 1 per cent. of coal for every 7·5° Cent. (13·5° Fahr.) of superheat. Thus a superheat of 100° Cent. (180° Fahr.) should permit of decreasing the coal consumption by fully 13 per cent.

In a paper read in November, 1909, before the Institution of Marine Engineers, Mr. A. F. White said that: "It was not easy to ascertain with any degree of accuracy the number of vessels now using superheated steam, but so far as could be ascertained, there were now afloat about 350 vessels of all sizes, from river and lake steamers up to naval cruisers, which were equipped with superheaters. Of these, Germany took the first place in numbers, having fitted out about 274 vessels, 188 of which were for canals, lakes, rivers, and coasting service, 81 sea-going steamers, and 5 vessels for the navy. Britain had about 40 vessels using superheated steam, including 4 naval cruisers. America could be credited with 20, of which 8 were naval vessels; and France with about 10 merchant ships."

Mr. White states that most of the German ships are fitted with the Schmidt type of superheater. He states that many experiments are being carried out with superheated steam, and expresses the opinion that the results will probably lead to the general adoption of superheated steam in marine practice. Mr. White states that although extra care is required and extra expense is entailed when marine engines work with superheated steam, the net commercial gain has been proved to be so great that ship-owners who have had many years' experiences with superheated steam now specify it for the machinery of new vessels.

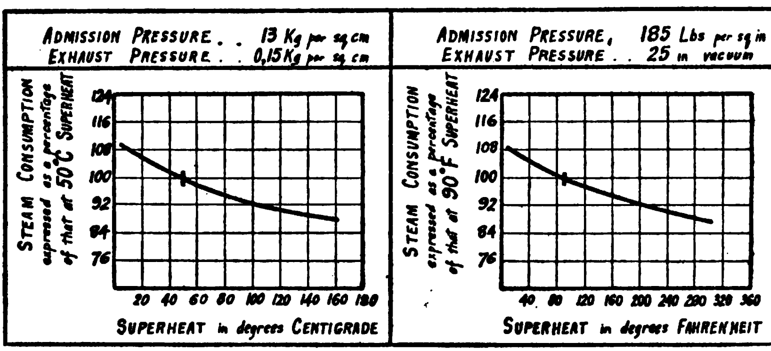


Fig. 14.—Curves showing the effect of Superheat on the Steam Consumption of Turbines.

In Fig. 14 are plotted, both in British and metric units, sets of curves based on values given in my treatise entitled, "Heavy Electrical Engineering" (Constable, London, 1908), which facilitate the estimation of rough values for the steam consumption of turbines at various superheats. The indications are admittedly only rough, but they show the order of magnitude of the advantage to be obtained by superheat. The table on p. 63 will also be found useful in investigating the question. It shows the ultimate temperature of the steam for a given pressure and a given number of degrees of superheat.

A little reflection shows that in view of the very considerable advantages of employing superheat in steam turbines (largely as the result of the decreased friction-loss of the rotor when running in dry steam), it is preferable to work with only moderate boiler pressure,

and obtain a greater amount of superheat for a given limiting temperature of the steam. This subject is discussed at greater length in the Author's "Heavy Electrical Engineering" (Constable and Co., London).

TABLE OF FINAL TEMPERATURES OF STEAM AT VARIOUS PRESSURES AND WITH VARIOUS DEGREES OF SUPERHEAT.

Absolute pressure in pounds per sq. inch.	Final Temperature of Steam in Degrees Fahrenheit (°F.) for the following Amounts of Superheat.									
	0° F.	20° F.	40° F.	60° F.	100° F.	150° F.	200° F.	250° F.	300° F.	350° F.
10	193	213	233	253	293	343	393	443	493	543
14·7	212	232	252	272	312	362	412	462	512	562
20	228	248	268	288	328	378	428	478	528	578
30	250	270	290	310	350	400	450	500	550	600
40	267	287	307	327	367	417	467	517	567	617
50	281	301	321	341	381	431	481	531	581	631
60	293	313	333	353	393	443	493	543	593	643
70	303	323	343	363	403	453	503	553	603	653
80	312	332	352	372	412	462	512	562	612	662
90	320	340	360	380	420	470	520	570	620	670
100	328	348	368	388	428	478	528	578	628	678
110	335	355	375	395	435	485	535	585	635	685
120	341	361	381	401	441	491	541	591	641	691
130	347	367	387	407	447	497	547	597	647	697
140	353	373	393	413	453	503	553	603	653	703
150	358	378	398	418	458	508	558	608	658	708
175	371	391	411	431	471	521	571	621	671	721
200	382	402	422	442	482	532	582	632	682	732
225	392	412	432	452	492	542	592	642	692	742
250	401	421	441	461	501	551	601	651	701	751
275	409	429	449	469	509	559	609	659	709	759
300	417	437	457	477	517	567	617	667	717	767

CHAPTER X

ELECTRICAL GEAR AS A MEANS FOR IMPROVING THE LOAD FACTOR

THE interposition of electrical gearing provides means for considerably decreasing the fuel consumption when applied to ships which run at varying speed. The largest Atlantic liners, such as the *Mauretania* and the *Lusitania*, perform their 3000-mile journey at the practically uniform speed of some 26 knots. But a war cruiser, while it must have capacity for a speed of, say, 25 knots, will usually steam at a speed which is more of the order of 14 knots. We have seen that for a vessel of a given displacement, the h.p. required varies roughly as the cube of the speed. Consequently, a war cruiser with machinery capable of driving her at a speed of 25 knots, will, for the cruising speed of 14 knots, only require:—

$$\left(\tfrac{14}{25}\right)^3 \times 100 = 17{\cdot}6 \text{ per cent.}$$

of her maximum power. With piston engines this need not necessarily be a serious matter. If a ship has three propellers, each driven by a separate engine, then, since the engines must have capacity for developing the power required at the maximum speed of the ship (*i.e.* at 25 knots), they will only be delivering 17·6 per cent. of their rated power when the ship is cruising at a speed of 14 knots. But piston engines are inherently adapted to low speeds and to varying speeds, and it is usually quite practicable to provide piston engines which, while economical at the ship's *maximum* speed, shall also have good economy in the neighbourhood of the ship's *cruising* speed. In fact, low speeds are inherently more appropriate for piston engines (and also, as we have seen, for propellers) than are high speeds. But if such a ship is fitted with steam turbines, then

while the steam consumption per h.p.-hour may be satisfactory at the maximum speed of 25 knots, it will increase rapidly with decreasing speed.

The *Topaz* and the *Amethyst* are two third-class British cruisers. The former is fitted with reciprocating engines; and the latter with steam turbines. These two vessels are of practically identical dimensions, and have the same displacement (3000 tons). Comparative tests have been made on these ships at various speeds. Certain of the results are shown in the following table:—

Speed in knots.	Steam consumption in lbs. per i.h.p. hr.	
	Topaz (piston engines).	*Amethyst* (turbines).
10	23·8	29·2
11	22·0	26·3
12	20·8	23·8
13	19·7	21·8
14	18·8	20·0
15	18·5	18·7
16	18·3	17·4
17	18·5	16·4
18	18·7	15·4
19	19·2	14·7
20	19·8	14·3
21	20·4	13·9
22	21·4	13·6
23	22·4	13·7

Thus, while at a speed of 10 knots the turbines consume 23 per cent. more than the piston engines, the consumption is the same in the two cases at about 15 knots, and is 39 per cent. lower in the case of the turbines when the speed is 23 knots.

This affords a typical illustration of the poor efficiency of a steam turbine when running below its designed speed. The *Amethyst's* turbines' speed at 23 knots is some 480 r.p.m., while at 10 knots their speed is some 180 r.p.m. Since the displacement is 3000 tons, we see from Fig. 1, on p. 7, that there will, at a speed of 23 knots, be required—

$$2{\cdot}4 \times \left(\tfrac{23}{20}\right)^3 \times 3000 = 11{,}000 \text{ i.h.p.}$$

(This result can also be read directly from the curves in Fig. 2, on p. 10.)

If, for such a ship, electric transmission gear were employed, there could be installed in the engine-room, four 3000-h.p. steam turbines, running at a speed of 1500 r.p.m. Each of these four turbines should drive a 2000-kw. continuous-electricity generator. Generators of continuous electricity are most satisfactory when designed for slow speeds. In this case they should be driven at a speed of, say, 300 r.p.m. by the interposition of mechanical gearing. We may safely take this gearing as of 98-per-cent. efficiency. Each of the three propeller shafts could be driven by four electric motors, and each of these motors would provide—

$$\frac{0{\cdot}95 \times 11000}{4 \times 3} = 870 \text{ h.p. at 23 knots.}$$

For all speeds up to some 12 knots it would only be required to have in circuit one motor on each shaft. With increasing speed more motors would be added, and the whole equipment would be in service when proceeding at full speed of 23 knots. The motors would be for a speed of some 200 r.p.m. (or even less) at 23 knots, and consequently the propellers could be of better and more efficient design than the 480-r.p.m. propellers of the *Amethyst.* Only at full speed of 23 knots would all four generating sets be run. For cruising speed it would suffice to run only one or two of the four generators, but all the three propeller shafts would nevertheless be driven.

Thus, firstly, we should at all speeds of the ship have the generating sets running in the neighbourhood of their rated load; *i.e.* the load factor of the plant would be high.

Secondly, the turbines would be of relatively small diameter, because of their high speed, and owing to their small diameter, could more appropriately employ superheat with consequent increased economy.

Thirdly, the turbines would, quite aside from the feature of superheat, have a lower steam comsumption than the *Amethyst's* turbines, for the reason that they are designed for a three-times-higher speed of revolution.

The result would be that while *at full speed,* the losses in the generators, mechanical transmission gearing, and motors would just about offset the gains; the net improvement *at cruising speeds* would be very striking indeed.

It should now be evident that the use of electrical gear permits of a much more important advantage than that of serving as a means of linking up high-speed steam turbines with low-speed (and consequently efficient) propellers. This additional important advantage consists in the introduction on board ship of the principle already highly developed in land practice, of operating the plant at high load factor.

A crucial requirement for the profitable operation of a land central station for the commercial supply of electricity is that the amount of generating apparatus running at any one time in the central station shall be proportional to the load on the station at that particular time. It is fatal to commercial success to have plant running at much less than its rated capacity. The load factor of an electricity supply station for combined lighting and power is rarely more than 0·33. That is to say, the average load for the 8760 hours of the year is only some 33 per cent. of the peak load; or, conversely the peak load is some three times the average load. In a central station requiring, at times of peak load, four 3000 kw. generating sets to be in service, there will, for a large portion of the time, be so small a load that only one of these generating sets suffices for the supply. During this large portion of the time, only one generating set (and its complement of boilers and auxiliaries) will be operated. If, during such periods of light load, all four generating sets were operated, each would be carrying less than one-fourth of its rated load, and not only would the fuel consumption be needlessly high, but such practice would also materially increase the annual outlay for repairs and renewals and for wages. Furthermore, there would obviously have to be provided a greater amount of spare plant, since there would be fewer opportunities for inspection, for cleaning, and for effecting minor adjustments and repairs, than when the plan is followed of concentrating the load on a minimum number of generating sets. It is hardly possible to overestimate the importance of this feature of land practice.

The amount of power required by a single ship of large size and high speed is commensurate with the power required in very important central station undertakings. Thus, the *Mauretania* and *Lusitania* each cross the Atlantic some thirty-three times in the course of one year, and some—

$$33 \times 5000 = 165{,}000 \text{ tons}$$

of coal are consumed under their boilers. There are not half a dozen electricity generating stations in Great Britain in which so large an amount of coal is consumed annually. In the generating station from which the Central London Railway is operated, the amount of coal burned annually is less than one-fifth of that burned annually on the *Mauretania*. The aggregate amount of coal burned annually in operating all the tramcars in Glasgow, Sheffield, and Newcastle, does not come up to the amount burned annually on the *Mauretania*. Incidentally it may be of interest to state that the amount of coal burned annually on the *Mauretania* would suffice to run fifty heavy express trains from London to Glasgow every day for one year. I have taken the *Mauretania* and *Lusitania* for these comparisons simply because they are the most widely-known ships. There are very many ships burning annually over one-third as much coal as the *Mauretania*. Consequently each of these many ships carries engine capacity equivalent to or greater than that provided in most land central stations.

As already pointed out, services where it is required that the ship shall always travel at practically its maximum speed, are not appropriate cases, from the load-factor standpoint, for employing electrical gear for the purpose of improving the load factor. But this does not exclude *all* ships making long voyages at constant speed. There is the very important consideration that the power required falls off roughly as the *cube* of the speed, and consequently a very small decrease in speed involves a very large decrease in power. I have already alluded to the rather extreme case of warships, which, while they have to be provided with engine capacity sufficient for high speed, make practically all their voyages at speeds of less than two-thirds of their maximum speed, and consequently require to develop less than $(0{\cdot}67^3) = 0{\cdot}3$ of their maximum thrust h.p.

Efforts are made to meet this case without resorting to electrical methods. Thus, on several warships, small cruising turbines have been provided in addition to the main turbines. At cruising speed, steam is only passed through these small cruising turbines, arrangements being provided whereby the rotors of the idle main turbines shall revolve in a low-pressure medium. But this is by no means the equivalent of completely shutting down the idle turbines.

Moreover, as repeatedly emphasized, steam turbines designed for low speeds are inefficient, and hence, even these small cruising turbines do not have by any means satisfactorily-low steam consumption.

Both the matter of cruising turbines and of an alternative arrangement, which is employed by the Parsons Marine Steam Turbine Co., were instructively discussed as follows by Engineer Vice-Admiral Oram in his Presidential address, on November 16, 1909, to the Junior Institution of Engineers:—

"All our original turbine ships were fitted with cruising turbines, in addition to those for use at the higher powers. The *Dreadnought*, for example, has four turbines on each side of the ship, counting as one turbine the low-pressure and low-pressure-astern, which are in one casing. Experience, however, has shown us that there are certain inconveniences attending the use of cruising turbines. They are economical, but being very often not in use, they are apt to be neglected, and not to receive the attention they require, and the few accidents that have occurred with turbines have practically all occurred in the cruising turbines. The question arose as to whether the increased economy due to their use is worth the extra complication, cost, and liability to injury, and the conclusion is arrived at that the balance of advantage and disadvantage is adverse to them, and they have not been fitted in recent warships. This view is the more readily taken, as the alternative recommended by Mr. Parsons appears to give us most of what we require without multiplication of turbines. This alternative is considerably to increase the expansion allowed in the main turbines at high powers, provision being made to obtain the maximum power by means of by-pass arrangements. This ensures greater economy at low powers than was hitherto obtainable with the main turbines, and by this system we gain simplicity and also a reasonable economy at such low powers. In certain classes of ships, however, where the radius of action at low powers is exceedingly important, owing to their limited coal or oil storage, as in torpedo-boat destroyers, two cruising turbines in series are fitted. In a typical example of this sort there are five turbines fitted on three shafts, again counting the low-pressure and low-pressure astern turbine as one. In this case the gain by the use of the cruising turbines in series is much greater, and is considered

to make up for the extra cost, weight, and complication involved, and they are being retained."

A better plan than to have cruising turbines for the low speed is to have piston engines of the required small capacity. This is for the reason that piston engines permit of much greater economy at low speeds than can be obtained with steam turbines. The main steam turbines should be reserved for the high speeds. These piston engines can then also serve for providing power for running astern, thus eliminating the necessity for reverse turbines. The British Admiralty's torpedo-boat destroyer *Velox* is an instance of a combination resembling in certain features the above recommendation. Her speed at full power is 36·6 knots. At this speed she is propelled exclusively by steam turbines. Of her four propeller shafts, the two outer are equipped with high-pressure turbines, while the two inner shafts each carry a low-pressure turbine and a reversing turbine. It would appear that it would have been a better combination to have entrusted the reverse running to the piston engines. The two piston engines, which are only employed at low speeds, are triple expansion, and each is rated at only 150 h.p. They assist in driving the two outer shafts, being fitted at the forward end, and driving the shafts through clutch couplings. They only play a small part in driving the vessel at the low-speed. When these piston engines are employed (*i.e.* for cruising speed), the steam is first carried through them, then through the two high-pressure turbines, and finally through the low-pressure turbines and to the condenser. The cruising speed is only 11·3 knots, and consequently the power required is only—

$$\left[\left(\frac{11{\cdot}3}{36{\cdot}6}\right)^3 = 0{\cdot}31^3 = \right] 0{\cdot}03$$

of that required for the maximum speed of 36·6 knots. The displacement of the *Velox* is 440 tons. From Fig. 1, on p. 7, we find that for a speed of 20 knots there will be required 5·5 i.h.p. per ton of displacement. Thus the curve indicates that at 36·6 knots there would be required—

$$\left(\frac{36{\cdot}6}{20{\cdot}0}\right)^3 \times 5{\cdot}5 \times 440 \doteq 14{,}700 \text{ i.h.p.}$$

But from the tests it appears that only 11,500 i.h.p. were necessary

at a speed of 36·6 knots. Consequently, at a speed of only 11·3 knots (0·03 × 11,500 =) 345 i.h.p. should (on the assumption of the same overall efficiency of engine and propeller at all speeds), be sufficient. This is a striking example of the disparity between the large amount of power which it is required shall be provided on a ship, and the small amount of power required to propel it at cruising speed.

The speeds of the shafts corresponding to various speeds of the *Velox* were as follows:—

Speed of ship.	Speed of shaft.
36·7 knots	1,180 r.p.m.
27·1 „	840 „
11·3 „	351 „

The arrangement of machinery employed on the *Velox* cannot be regarded as rational, and it has not been repeated on other boats. In a paper by Mr. Parsons, entitled, "The Combination System of Reciprocating Engines and Steam Turbines," read on April 9, 1908, before the Institute of Naval Architects, the following reference is made to the *Velox*:—

"In the year 1902, the combination of reciprocating engines exhausting into turbines was first put to a practical test in H.M. destroyer *Velox*. In this vessel, two small reciprocating engines were fitted for cruising purposes, of such power that, in combination with the main turbines, they would give an economical consumption at the speeds of 11 to 13 knots, the usual cruising speeds at the time the *Velox* was built. The arrangement of the machinery consisted of one main high-pressure and one low-pressure turbine on each side of the vessel, each driving a separate shaft, or four shafts in all. A small reciprocating engine was coupled at the forward end of each of the low-pressure turbines. For speeds up to about 13 knots, steam was admitted to the two reciprocating engines, and expanded down to about atmospheric pressure; it then passed through the high-pressure, and thence through the low-pressure turbines, to the condenser. This combination gave excellent results at these cruising speeds. For speeds above 13 knots, however, the reciprocating engines had to be cut out, and steam admitted to the turbines alone.

With the advance of naval efficiency, the cruising speeds of war-vessels have been increased, and in vessels subsequent to the *Velox*, additional high-pressure turbines have been fitted, an arrangement which permits of good economy over a wide range of cruising speeds."

A better plan than that adopted on the *Velox* is that employed on two steam yachts, the *Caroline* and the *No.* 1125, built by Messrs. Yarrow and Co., Ltd. The design provides three shafts. The outer shafts are driven by steam turbines, running, in the case of the *Caroline*, at 1500 r.p.m. The aggregate capacity of the two steam turbines on the *Caroline* is 2000 h.p. The centre shaft is driven by a 250 b.h.p. piston engine, which suffices for low speeds and for astern running. No astern turbines are provided. The vessel's forward speed is 26·4 knots, and her astern speed is 10 to 14 knots. The turbines, and also the piston engine when it is running, take steam from the boilers and deliver exhaust to the condenser. The high-pressure turbine is on one side-shaft, and the low-pressure turbine on the other. The *Caroline's* overall length is 152 ft., her draught is 5 ft., and her displacement is 140 tons. The turbine machinery weighed 7·7 tons.

On some trial runs, on January 19, 1904, the following results were obtained:—

Speed of vessel (knots).	R.p.m.			Admission pressure to high-pressure turbine (lb. per sq. in.).	Condenser vacuum (inches of mercury).
	Piston engine.	High-pressure turbine.	Low-pressure turbine.		
12·0	369	393	395	0	26·8
15·5	411	688	687	5	28·0
18·7	441	955	994	50	28·0
21·9	475	1,172	1,357	100	27·2
25·0	516	1,455	1,657	145	26·9

At the 12-knot speed the reciprocating engine alone received steam, while the turbines revolved idly, due to the action of the water on their propellers. The other trials were made with progressively increased steam pressures supplied to the high-pressure turbine.

Excellent results as regards coal consumption have been obtained by high-speed steam-turbine boats when running at their high speed,

but at half this speed the turbine boats are greatly inferior to similar boats equipped with piston engines. As bearing on this statement, attention may be directed to the case of the turbine-driven torpedo-boat destroyer *Eden*. She has an overall length of 220 ft., and her displacement is 565 tons. Her speed is some 26 knots. She is equipped with turbines of an aggregate capacity of 7000 h.p., and has three shafts. On four-hour tests, at a speed of 26·2 knots, the consumption of coal was 7·45 tons per hour. At half-speed she consumed 1·3 ton per hour. Several boats, practically identical with the *Eden* as regards size and speed, have been equipped with piston engines. The only essential difference is that they have two shafts against the *Eden's* three shafts. The average coal consumption of these boats at a speed of 25·3 knots is 6·7 tons, or, say, 7·2 tons at 26·2 knots. Thus, at a speed of 26·2 knots, the turbine boat shows practically the same coal consumption as the piston-engine boat. But at half-speed the coal consumption of the piston-engine boats is only some 0·5 ton per hour, or less than half that of the turbine boat. The *Eden* was launched in 1903, and considerable improvements have been made in turbine boats since that date. But turbine boats of this size and speed, while they give good results at full speed, always show up relatively very badly at low speeds.

The turbine is an appropriate prime-mover for high-speed vessels which only rarely have to travel at low speeds. It has come to be fairly generally accepted that the turbine is not an appropriate prime mover *for direct-coupling to the propeller shaft* for ships whose speeds are below some 16 knots, or which, while having capacity for higher speeds, travel a great deal at low speeds. Mr. Parsons, however, has made more sweeping claims for the turbine as a prime mover for ships. Thus, in 1903, in the discussion of a paper which he read before the Institute of Naval Architects, Mr. Parsons says—

"In regard to the present limits to the application of the steam turbine, I may say that we should be quite ready to deal with a set of engines of 10,000 h.p. and 10 knots speed, which is just on the line of demarcation; but it is very much easier to design efficient turbine-engines for a vessel of 20 knots and 10,000 h.p., and the advantages would be very much greater in the latter case. The line of demarcation would run at present at about 18 knots and 2000 h.p., and 15 knots and 5000 h.p., and 12 knots and 10,000 h.p. There are

special cases of yachts and shallow-draught vessels where considerable advantage over ordinary engines would result in the case of even smaller horse-powers and slower speeds than these."

The case of a warship is an instance where very high speeds, such as are best provided by steam turbines, are required, but where it is also of great importance that the coal consumption per h.p.-hr. should also be low at low speeds. It appears to be a fact that the statement which has been made that, in warships, nine-tenths of the coal is burned at cruising speed is correct. Thus, the turbine's rather voracious appetite for steam when running at speeds considerably below the designed maximum speed, constitutes a very grave disadvantage, and affords a legitimate and strong argument for employing electric propulsion on warships. While at full speed the electrical apparatus may not reduce the coal consumption, it will effect a very great improvement in the economy at cruising speeds. Any decrease in the coal consumption correspondingly increases the ship's radius of action. The direct drive by steam turbines results in a much smaller radius of action for a warship than corresponds to the radius of action of the equivalent piston-engined warship.

Even merchant ships require on frequent occasions to travel at reduced speed. As instances of such occasions, foggy weather may be mentioned, as also voyages in which inland navigation in rivers and canals is combined with open sea routes.

Prof. Rateau has stated the following view:—"There is, therefore, a lower limit of speed below which the use of turbines cannot be recommended. I have already expressed the opinion that this limit is in the neighbourhood of 20 knots. I am aware that certain ships now under construction for transatlantic service, and of a proposed speed of 17 knots, are being fitted with turbine engines, but the future will show how these will turn out."

The American scout cruisers *Birmingham, Salem,* and *Chester* afford further striking examples of the wide difference in the amount of power required at top speed and at cruising speeds. A great deal of interesting information has been published about these three boats. Concise digests have appeared in the following issues of the *Times* "Engineering Supplement": April 1, 1908; July 29, 1908; Sept. 21, 1910. The *Birmingham* is piston-engined. The *Salem* has Curtis turbines, and the *Chester* has Parsons turbines. The

Birmingham and *Salem* were built and engined by the Fore River Company of Quincy, Massachusetts. They are practically identical in all respects except as regards their propelling machinery. The *Chester* was built at the Bath Iron works, and differs from the *Salem* in addition to difference in types of turbine, in that the *Chester* has four independent propeller shafts driven by six main and two astern turbines, while the *Salem* has only two propeller shafts with one turbine per shaft. All three boats are 420 ft. long. With 450 tons of coal on board, the displacement is about 3750 tons, and the guaranteed speed is 24 knots. But the bunker capacity is 1250 tons, and with this amount of coal in the bunkers, the displacement is some 4550 tons. The estimated power was some 16,000 i.h.p. The contract price for the hull and machinery was about £320,000 per boat. Eight piston-engined British scouts, whose lengths are from 360 ft. to 374 ft., whose displacements are from 2600 tons to 3060 tons, and whose engine capacities were ascertained on test to be from 14,500 i.h.p. to 17,000 i.h.p., at a speed of some 25·5 knots, cost about £270,000 each. Thus these American and British scout cruisers work out at a cost of close to £100 per ton of unloaded displacement. The earlier reports appeared to indicate that even at the cruising speed of only 12 knots the turbine boats showed lower coal consumption than the *Birmingham*. But in the *Times* "Engineering Supplement" for Sept. 21, 1910, the data of a recent report of the Navy Department of the United States[1] is discussed, and the contrary result is stated to have been obtained. The writer of the *Times* article states: "The difficulty of measuring the shaft h.p. in the *Salem* and *Chester* is admitted, and it is said that it may lead to an error of 20 per cent. at low speeds; but at high speeds the figures are thought to be right to within 2 per cent. In point of economy it was found that up to a speed of 20·6 knots, corresponding to half the designed full load of her engines, the *Birmingham* was the most efficient of the three vessels; but above 22·3 knots she became the least economical of them." It would, however, appear that there was not, as was the case with the British torpedo-boat destroyers discussed on p. 73, any *very marked* inferiority of the turbine-driven boats at low speeds. Indeed, all three boats appear to have given remarkably similar results. For a four hours' trial at

[1] See *Engineering News* for Sept. 1, 1910.

full speed of 24·3 knots, the *Birmingham's* engines made 191·7 r.p.m., and worked at 15,540 i.h.p., consuming 1·92 lb. of coal per i.h.p. per hour. On a 24 hours' trial, at a speed of 22·5 knots, her engines ran at 172 r.p.m. and developed 10,760 i.h.p. The corresponding coal consumption was 1·91 lb. per i.h.p. per hour. A further 24 hours' trial at the cruising speed of 12·2 knots required an average of 1600 i.h.p. with the engines running at 91·4 r.p.m. The coal consumption was 2·89 lbs. per i.h.p. per hour. Thus we have—

Speed of vessel, in knots.	Speed of engines, in r.p.m.	I.h.p.	Coal consumption, in lbs. per i.h.p. per hour.
12·2	91·4	1,600	2·89
22·5	172·0	10,760	1·91
24·3	191·7	15,540	1·92

Thus at one-tenth load the coal consumption per i.h.p. per hour is 56 per cent. higher than at full load. But if, in the engine-room, we had had, say, five large turbine-driven electricity generating sets, supplying power to electric motors coupled to the propeller shafts, we should only have had one of these sets running for the cruising speed, and the coal consumption per i.h.p. per hour would not have been materially greater than for full speed.

This is admirably shown by Emmet, in a paper entitled, "Proposed Applications of Electric Ship Propulsion," read before the American Institute of Electrical Engineers on Feb. 14, 1911 (see p. 28 of vol. 30 of *Proc. Am. Inst. Elec. Engrs.*). Mr. Emmet works out an alternative for the equipment of the U.S. battleship *North Dakota.* In his alternative, he employs two 12,000-kw. turbo-driven alternators delivering power to four 7000 h.p. induction motors. For speeds ranging from 12 to 15 knots, one generator and two motors are running; from 15 to 21 knots, two generators and four motors are running. Furthermore, the number of poles of the motors are altered at various stages and in such a way as to conduce to economy. Emmet works out a curve for the steam consumption per b.h.p. per hour, and compares it with the steam consumption for the *North Dakota,* which is a 25,000-h.p. battleship propelled by two Curtis turbines. At 21 knots, the *North Dakota's* propellers are driven at the high speed of 260 r.p.m., in order to avoid employing for the

steam turbines a speed too far below economical limits. Thus the propellers are designed for an uneconomically high speed, and the steam turbines for an uneconomically low-speed. In Mr. Emmet's design, on the contrary, the 21-knot speed corresponds to a propeller speed of only 160 r.p.m. Mr. Emmet's 12,000 kw. turbines run at the high speed of 900 to 1200 r.p.m., even when the ship is travelling at cruising speed, whereas at 12 knots, the *North Dakota's* turbines run at only 145 r.p.m. Mr. Emmet's design further provides for always operating the propelling machinery at a high load factor. The results are as follows:—

Speed of ship, in knots.	Steam consumption in lb. per b.h.p. hour.	
	North Dakota, with Curtis turbines direct-connected to the propellers.	Emmet's alternative design, with electric propulsion.
12	20·5	13·2
16	17·0	13·4
18	15·2	11·8
19	14·3	11·3
20	13·5	11·3
21	13·0	11·3

ROT

The *North Dakota* and the *Delaware* are sister ships. The former is equipped with Curtis turbines on two shafts, and the latter is equipped with triple-expansion piston engines. Their displacement is 20,000 tons. At p. 823 of *Engineering*, for December 17, 1909, it is stated that the contract price for hull and machinery was £875,000 (or £43·2 per ton) for the *North Dakota*, and £797,000 (or £39·9 per ton) for the *Delaware*.

CHAPTER XI

INTERNAL-COMBUSTION ENGINES FOR SHIP PROPULSION

THE economic advantages possessed by the electrical proposition in the matter of improving the load factor, for ships running at speeds materially below their maximum speed and also in the matter of reversing, are not remotely approached by any alternative proposition. These load-factor advantages, however, do not have any more significance for turbine-driven ships than for ships driven by internal-combustion engines. In fact, they are decidedly more in evidence when internal-combustion engines are under consideration. While land gas engines have been developed for very large powers, they are not yet immune from elements of unreliability which would be fatal to their use for propelling ships. The future doubtless has in store for us very large gas engines possessed of thoroughly reliable characteristics, but I do not believe that the statement will be challenged that the *near* future will not signalize the advent of such engines. In small powers the gas engine has been brought to a high state of development, and constitutes a highly efficient means of power production. This is true (probably in even greater degree) of the Diesel oil engine. But as regards reversing, neither gas nor oil engines have as yet been developed with suitable characteristics. Reversible engines are available, but in obtaining the feature of reversibility, either economy or freedom from complications, or other desirable features, have to some degree been sacrificed.

In view of this state of affairs it would appear that the only sound means as yet devised, by which advantageous use may be made of the high efficiency of the gas engine in ship propulsion, is to introduce electrical gear between the engines and the propellers, and thus operate the gas engines non-reversibly, and to only employ

such relatively small capacities of individual engines as have been developed to a good degree of reliability. Complete satisfaction as regards efficient and powerful reversibility is afforded by continuous-electricity motors. When an electrical transmission system is embodied in the propulsive machinery, the relatively small powers of the individual generating sets constitute no serious disadvantage, since these small individual powers may be efficiently integrated at the electric motors which drive the propellers.

In fact, although the most attractive feature of the electrical proposition appeared, a very few years ago, to relate to reconciling the high-speed characteristic inherent to efficient steam turbines with the low-speed characteristic inherent to efficient propellers, the investigations and discussions of the last few years have brought prominently to the foreground the wide-reaching importance of the load-factor consideration, and the consideration of obtaining effective reversal. I am of opinion that the powerful accelerating and manœuvring capacity which may be provided by the interposition of electrical gear will be the next feature in the chain of advantages which will soon be recognized as a peculiar and exclusive attribute of the electric drive.

The chief credit for recognizing in its wide bearings the load-factor advantages associated with the electrical proposition belongs, in my opinion, to Mr. Henry A. Mavor, who has for several years devoted a large amount of study and investigation to the application of electricity to ship propulsion. In a paper entitled, "Marine Propulsion by Electric Motors," read by him on Dec. 7, 1909, at the Institution of Civil Engineers, Mr. Mavor says: "Electricity offers the most convenient means—and indeed, on a large scale, the *only* means—by which speed adaptation, together with reversal of direction and cumulative application of power, independently of speed, can be combined with an approach to full-load economy of fuel at all loads. The possibilities apply, of course, to the association of electricity with any kind of power generator, whether driven by steam or by the internal combustion of gas, oil, or spirit. While the internal-combustion engine is still comparatively small in size, yet this type of plant, combined with electric transmission, seems to offer a good prospect of economy." In this paper Mr. Mavor works out some cases of vessels for which he estimates

the relative costs of electrical and direct propulsion. Amongst these are cases in which he employs respectively Diesel oil engines and producer gas engines.

In the preceding chapter I considered the application of electric drive to a British third-class cruiser. I assumed the employment of steam turbines running at the constant speed of 1500 r.p.m. and driving 300 r.p.m. continuous-electricity generators, the speed reduction being provided by double helical gearing of at least 98 per cent. efficiency. Since the speed of 300 r.p.m., which I stated was appropriate for the continuous-electricity generators, is also an appropriate speed for Diesel engines, the replacement of the steam turbines by oil engines obviates the necessity for the speed-reduction gear. The 300-r.p.m. Diesel engines will, per shaft h.p., be much heavier and more expensive than the 1500 r.p.m. steam turbines; but the elimination of boilers and the suppression of any speed-reduction gear, results in an oil-engine alternative which is cheap and compact. Moreover, the fuel costs will be greatly reduced, although the fine workmanship in the Diesel engine will doubtless run up the wages item associated with attendance, inspection, and repairs. Whereas for the steam-turbine drive I proposed four 2000-kw. generating sets, the use of the Diesel engine alternative would make it deirable to have further subdivision in the power plant, and ten 800-kw. sets would be appropriate. The motor equipment would be the same as in the first case. This is my own estimate, and it must not be inferred that Mr. Mavor, in his paper, proposed such large units. Mr. Mavor only described the application of the Diesel engine to still smaller vessels, where the total power required only amounted to some 1000 to 2000 h.p. But while until recently the output per cylinder was, in the Diesel engine, usually kept down to less than 100 h.p., many of the newer designs are worked out for an output of from 150 to 200 h.p., and even more, per cylinder. A 10,000 h.p. Diesel engine is being manufactured by the Augsburger Maschinenfabrik of Nuremberg.

In the *Times* "Engineering Supplement" for August 3, 1910, are given certain data regarding the Diesel engine equipment which it is reported that the Hamburg-American Company are fitting in an Atlantic liner of 9000 tons displacement. The equipment is stated to have been ordered by the Hamburg-American Company from

Messrs. Blohm and Voss of Hamburg. The vessel's speed is to be only 12·5 knots. The vessel will, it is reported, be fitted with two Diesel engines, each of about 1500 h.p. capacity, and constructed in Germany. The note continues as follows: "The twin propellers, which will in proportion be smaller than those on a steamer of the same tonnage, will work at about 150 r.p.m. The fuel employed will be petroleum residue, of which the Diesel engine requires ½ lb. per b.h.p. hour, as compared with about 2 lbs. of coal with the best steam engine; thus it is expected that a saving of 75 per cent. will be made in the amount of fuel to be carried. The cost of the petroleum residue on this side of the Atlantic is about 40*s.* to 45*s.* per ton." In commenting upon this report, in the next week's issue of the *Times* "Engineering Supplement," "An Engineering Correspondent" writes: "The speed of revolution (150 r.p.m.) is rather high, and probably there will be some loss in propulsive efficiency as compared with a reciprocating steam installation for the same boat; but the economy of oil engines is so far in advance of that of steam plant that this loss will be almost negligible. As a similar boat is to be built at the same time with an ordinary steam engine equipment, competitive trials will be possible, and should provide some very valuable data." Later in his article this "Engineering Correspondent" writes: "There is so much to gain in economy by employing Diesel engines for ship propulsion that, should the direct drive be found unsatisfactory, there is considerable likelihood of a purely electro-mechanical system coming to the fore, which for other reasons possesses many advantages. There would, of course, be some loss in transmission of power, but, on the other hand, engines of the ordinary land type would be used, with a higher efficiency than can ever be attained by the reversing machines; and in any case the superiority over the present steam-engine drive would be large, since the same power could be developed with about one quarter the weight of fuel." It is stated in that article that a large firm on the Continent is about to instal a four-cylinder 1000 h.p. Diesel engine on a twin-screw cargo boat. This engine is of the two-stroke type, and is reversible. The normal speed is 220 r.p.m., but the engine can, by throttling the supply of oil, be run at any speed from 250 r.p.m. down to 40 r.p.m. The author states that "the fuel consumption is naturally somewhat higher than with the ordinary

type, and is reckoned to be something approaching 20 per cent. in excess."

Diesel engines cost from £13 per b.h.p. in the smaller sizes, down to £9 per b.h.p. in the largest sizes. The weights of two-stroke Diesel engines, when reduced to a reference basis of 300 r.p.m., range from some 110 lbs. per b.h.p. for 200-h.p. sizes down to some 80 lbs. per b.h.p. in 800-h.p. sizes. One b.h.p. hour is obtained at a consumption of some 0·6 lb. of crude oil, the precise figure depending upon size, type, speed, and other details peculiar to each case.

Gas Engines for Ship Propulsion

Gas engines share with oil engines the fault of being very deficient in the matter of reversing, and are not *yet* by any means so reliable as steam prime movers. They are not yet capable of being built of nearly so great an output per unit as is the case with steam turbines. For these reasons, as also for the other reasons set forth at an earlier section of the present chapter, the intermediation of electricity is especially appropriate. Moreover, although gas engines permit of securing great economy of fuel at full load, the consumption per b.h.p. hour at light loads is much greater than at full load. Gas engines are large and expensive, and, consequently, the additional cost of the electric generators and motors required to obtain the further advantages of satisfactory reversal and of high-load factor does not involve by any means so great a *percentage increase* in the initial capital outlay as in the case of turbine-driven ships. If considerations of the high initial capital expenditure are not of sufficient importance to prevent the adoption of the gas-engine proposition, the very great further advantages obtained by the addition of the electrical gear should be taken into serious consideration. It would appear, as Admiral Oram has recently stated, that "four-cycle gas engines, with producers and cleaning plant, must generally be heavier than steam engines and boilers." Admiral Oram cites the case of H.M.S. *Rattler*, in which, after removing the original steam plant, Messrs. Beardmore fitted equivalent gas-engine and anthracite producer plant. This is the largest marine gas-engine installation which has yet been fitted in Great Britain, and Admiral Oram states that "a comparison with the

steam engine which was taken out of this vessel shows that the h.p. obtained per ton with the latter was about twice that obtained with the former." Admiral Oram explains that although this is comparing "the steam-engine practice of 1886 with the gas-engine practice of twenty years later," nevertheless, since "the gas engine fitted in this ship was an experimental installation," it is probable that a future one would "make a more favourable comparison with the steam engine." After discussing further aspects of the subject, including the objections and difficulties associated with reversible gas engines, Admiral Oram concludes that, "Generally, the combination of non-reversible gas engines with electrical transmission is the most promising direction for the utilization of this system" (*i.e.* gas engine and producer plant).

A chief difficulty in the way of the introduction of gas engines on board ship relates to the circumstance that anthracite coal can only be obtained at a very few of the world's leading ports. This circumstance is emphasized by Admiral Oram, and he reasons that, since no producer using bituminous or semi-bituminous fuel "of a type suitable for marine purposes" has yet been perfected, he sees no prospect of the early introduction of marine gas engines.[1] The fuel

[1] During the stage of proof-reading of this treatise, Mr. J. E. Dowson has (April 28, 1911), read his paper on "Gas Producers" before the Institution of Mechanical Engineers. In this paper Mr. Dowson publishes data of his gas producer for bituminous fuels, from which it appears that nearly as good results can be obtained from bituminous fuel of a calorific value of 13,400 British thermal units, and costing (delivered at West Bromwich) 8 shillings per ton, as from anthracite coal, costing 23 shillings per ton. Mr. Dowson states that "on an average of several months the consumption of bituminous coal was about the same as with anthracite, namely, about 1lb. per indicated horse power, including all stand-by, cleaning, and starting losses. The gas has no tar when it leaves the producer, and none is found in the scrubbers or overflow water; Messrs. Kenrick have stated that the gas from the bituminous coal is as clean as the anthracite gas previously used. They clean the engine valves only once in about three months." The above results relate to a plant "now serving 13 gas engines which were previously working with anthracite pressure gas." In commenting editorially on this paper, the *Electrical Review* for May 12, 1911, states, on p. 742: "It has long been recognized that in theory and practice the gas producer has lagged far behind the gas engine, which, with the aid of blast furnace gas, has been developed to a high degree of mechanical perfection. It is true that the large gas engine is still an expensive and complicated machine, and that there is abundance of room for its improvement in the direction of cheapness and simplification, features which the small gas engine already possesses to a marked degree; but it is a thoroughly practical, efficient and reliable prime mover. . . . However, in view of the results announced by Mr. Dowson, there is ground for hoping that in the near future the necessity of

consumption in a steam-turbine installation is stated by Admiral Oram to be "approximately about 50 per cent. greater than in an internal-combustion engine installation using similar fuels."

Mr. Mavor, in working out the case of a 770-shaft h.p. cargo-vessel, in which the gas engines drive a variable-speed electric motor, states that, "The fuel saving would depend, of course, on the relative price of anthracite, which is required for the producer, and of the ordinary bituminous coal which might be used for the boilers; but taking anthracite coal at 20 shillings per ton in each case, the fuel cost of the gas plant would be about two-fifths of the cost for the normal steam plant."

In the particular example worked out by Mr. Mavor, the power of three gas engines was concentrated in one motor of a type which he has invented, and which he terms a "multiple-motor." The principles of this motor will be explained in a subsequent chapter. Mr. Mavor expressed the opinion that for ship propulsion, "the use of the gas engine without the intervention of electric motors, was not a proximate possibility." He did not consider that one could "contemplate with serenity going to sea in a single-propeller ship driven by a *single* gas engine; it would not be wise to do it. On the other hand, to have *three* gas engines and one propeller was a proposition of an altogether different kind. One gas engine could be shut down and the other two used." Mr. John Reid, of Montreal, endorses Mr. Mavor's plan, and states that "while a single gas engine would almost inevitably result in stoppage and breakdown from trivial causes, a three-unit arrangement provides an almost perfect safeguard against an entire breakdown of the propelling machinery." On the other hand, Mr. George Hart, in discussing this particular feature of Mr. Mavor's proposals, has taken an unfavourable view. He writes as follows: "When the power is developed by internal-combustion motors, the employment of an electric motor as an intermediary is a question which calls for close investigation. It is so simple a matter to disconnect one or several cylinders of such apparatus that it seems generally useless to resort to the employment of electricity. The

employing costly anthracite will be obviated, and that it will be found possible and practicable to use bituminous coal at one-third the price. The new producer apparently generates gas which is as free from tarry vapours as that derived from anthracite, and it can be worked successfully in both large and small sizes."

loss of output resulting from this disconnection of cylinders is assuredly less than that due to the supplementary transformation necessitated by the employment of electricity."

A small cargo vessel of 120 ft. length and 22 ft. beam is at present being fitted with anthracite producers and a six-cylinder vertical gas engine for an output of 180 b.h.p. at 450 r.p.m. The producer plant (which is in duplicate) is being constructed by the Power-Gas Corporation of Stockton-on-Tees. Messrs. Eltringham & Co., of South Shields, are building the vessel. The propeller-shaft is driven at a speed of 120 r.p.m. by interposing Föttinger hydraulic gearing (see p. 51) between the 450-r.p.m. engine and the *low*-speed propeller shaft. The Föttinger gear not only permits of adopting an efficient propeller speed, but it also permits of astern running without reversing the engine. The bunker will have capacity for 12 tons of anthracite. It is estimated that the coal consumption will be from 1·0 to 1·5 tons per day, whereas if compound steam engines had been employed, the consumption would have been some 3·5 tons per day. Further information regarding this boat is given in the *Times* "Engineering Supplement" for August 10, 1910. In this same issue it was announced that a steel-built vessel of 54 ft. length, and employing electrical transmission in combination with gas engines and suction-gas producers in accordance with designs by Mr. Mavor, would shortly be launched by Messrs. McLaren Brothers, of Dumbarton. It should again be emphasized that the interposition of electrical transmission introduces at the same time the feature of effective reversal. Hence comparative results on the two ships above described, the one employing Föttinger hydraulic gearing and the other employing electrical gearing, would possess very considerable interest. The vessel built by Messrs. McLaren Brothers, to Mr. Mavor's design, is named the *Electric Arc*, and was launched in February, 1911. She is equipped with a four-cylinder vertical Crossley gas engine of some 45 b.h.p.,[1] coupled to a double-periodicity electric generator, which in turn drives a multiple motor which drives the propeller. The multiple motor is described on p. 113.

[1] At a time when the proof-reading of this treatise is well advanced, there has appeared on pp. 767 and 768 of *Engineering* for June 9, 1911, an illustrated description of this boat, which is now being tested. Certain particulars, taken from this article, are given at the close of this chapter, on p. 91.

The Mirrlees-Day System of Ship Propulsion

In the earlier part of this chapter, the Diesel engine has been discussed, and it is as well at this point to allude to a combined method of driving ships which is put forward by the exploiters of a certain make of Diesel engine. This method was briefly described by Mr. Charles Day in a lecture on "The Diesel Engine," delivered at the Municipal School of Technology, at Manchester, on March 8, 1909. The latter paragraphs of the lecture were reported as follows: "Attention was drawn to some of the advantages to be derived from the adoption of the Diesel engine for marine propulsion. All forms of internal-combustion engines work with a lower fuel consumption than do steam engines. In the case of the Diesel engine, the weight of fuel per b.h.p. per hour is not more than one-fifth the weight of fuel used with a really good-class steam engine of the same power, when account is taken of the steam used in connection with condenser, feed pumps, and other auxiliaries. The reduced consumption of fuel per b.h.p.-hr. means a considerable reduction in tonnage of fuel carried, which in turn means that a given vessel is able to carry a greater proportion of paying cargo. As to the matter of space, whilst it perhaps cannot be asserted that gas engines with their producers would occupy less space than steam engines and boilers, there is no doubt that *oil* engines would occupy considerably less space. Also the oil would be more easily put on board, and as a ton of oil occupies less space than a ton of coal, and, further, as the oil can be stored in double bottoms and other places not suitable for storing coal, there is a considerable amount of bunker-space saved by the adoption of oil. Another point in which the Diesel engine may possibly prove to have an advantage over the gas engine is that the Diesel engine will work equally well, and without alteration, with almost any combustible oil, whereas gas producers, if supplied at different ports with coal of widely varying quality, might not work satisfactorily. *The great disadvantage which all internal-combustion engines suffer from is in connection with speed variation and reversing.* A steam engine running at, say, 200 r.p.m. can be controlled almost perfectly down to 2 or 4 revolutions per minute in either direction. This is not attainable with an internal-combustion engine,

except by discontinuing at slow speeds to run it as an internal-combustion engine, and instead, running it as a compressed-air engine. Whether this will be entirely satisfactory, experience alone can show. To meet all the conditions which one can imagine might arise in *foggy weather* or in *crowded harbours*, it would seem probable that *the air storage receivers would have to be inordinately large.*" The lecturer gave it as his opinion, that by far the best course would be to adopt engines running in one direction, and to reverse the propeller shaft by means of either mechanical reversing gear or electrical. For powers up to 150 h.p. he recommended mechanical reversing gears. For above 150 h.p. electrical would be preferable at present, and the scheme he recommended was described as follows:—

"The engine is to run always in one direction, but its speed may be controlled from full to half-speed, or even lower. At half-speed,

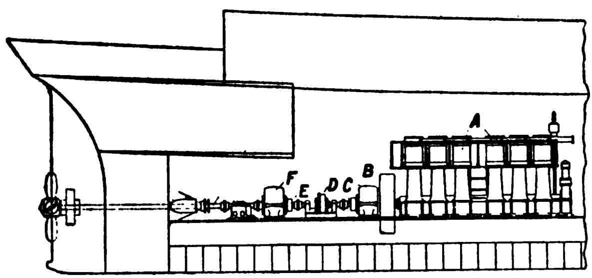


FIG. 15.—The Mirrlees System of Propelling Ships by Internal-Combustion Engines.

the power is one-eighth of the full-speed power, as the power to propel a ship varies as the cube of the speed. When driving ahead at all speeds from half to full speed, the engine is coupled direct to the propeller shaft by means of a clutch. Below half-speed, and for reversing, the clutch will be disconnected, and the propeller shaft driven electrically, there being a dynamo on the engine crank-shaft and a motor on the propeller shaft. By this scheme, the electrical portion need only be one-eighth the full power of the engine, or if some little margin is given, say, one-sixth or one-fifth. Many big schemes of marine propulsion by internal-combustion engines have been talked of, but, in the opinion of the lecturer, success would be more quickly attained by not being too ambitious at the commencement, and that it would be better, for the first year or two, to supply

internal-combustion engines to ships requiring only a few hundred h.p. than to commence with ships requiring several thousand h.p."

The method of ship propulsion above indicated by Mr. Day is the subject of his British patent No. 6126, of 1909. Fig. 15 is reproduced from this patent. A is a six-cylinder internal-combustion engine coupled to a dynamo, B. The rotor shaft, C, of the dynamo—or the engine shaft—is adapted to be connected by a clutch, D, with the shaft E of the electric motor F, which is connected with—or formed integrally with—the propeller shaft. The patent goes on to state that the internal-combustion engine may be constructed and arranged to be capable of being varied in speed from that required to propel the ship at full speed to that required to propel it at half-speed. Thus, at all ahead-ship speeds, direct driving may be employed; but, for speeds less than half, the electrical transmission may be employed, the motor F, receiving electrical energy from the dynamo B. The electrical drive may also be employed for reversing, the astern speed being not greater than half the full-ahead speed, suitable electrical switches and gear being provided.

At p. 283 of vol. 179 of the *Proc. Inst. Civil Engrs.* (February, 1910), Mr. H. S. Russell, in discussing this system, pointed out that, "on emergency, such as to avoid collision, etc., it was possible, while operating the propeller electrically, to increase the engine speed to its maximum. The dynamo and motor were, for the time, overloaded, but were capable of withstanding this overload for a reasonable period. The advantages of this system were that the weight, space, and cost of the electric portion of the installation were reduced to a minimum, while losses in transmission, which were inseparable from a purely electric transmission, were avoided at all speeds above half-speed ahead. The astern power provided, would, it was considered, meet all requirements. It should also be borne in mind, in regard to speed control, that, in ordinary circumstances, there was no advantage in being able to reduce the speed of the propeller below the limit imposed by satisfactory working of the rudder—that was, below the amount required to keep steerage-way on the vessel. If the view expressed in the foregoing, namely, that it was not necessary to instal in any vessel sufficient power to enable her to go full speed astern, were accepted, it reduced the electrical difficulties in installing motors of large power."

Mr. Russell made the point that while the electric drive had often been advocated, largely with a view to driving the propeller by a motor revolving at a lower speed than the generator—in other words, to overcome the objection of the high speeds of steam turbines, this objection did not apply to internal-combustion engines. He stated that, "At present, all internal-combustion engines were of the reciprocating type, and ran at speeds about the same as those of reciprocating marine engines. They could therefore be coupled direct to the propeller shaft without loss of efficiency, and without the use of electric motors. The questions of reversing and speed variation, however, entered largely into the problem of marine propulsion. Diesel and other types of oil and gas engines had been fitted in small vessels of moderate powers, and had either been made reversible or

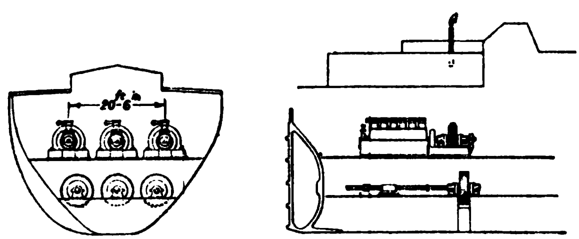


FIG. 16.—Triple-Screw Cargo Vessel with Electric Motors of 840 h.p. driven from Diesel Engine Sets.

had been coupled to reversing propellers or reversing clutch gears. Probably the relatively small size of internal-combustion engines, as compared with steam engines, had prevented the application of such devices to larger vessels. As far as Diesel engines were concerned, larger sizes were now available, and engines giving about 150 h.p. per cylinder had been made in England."

At p. 32 of the *The Electrician* for June, 1910, Engineer-Lieutenant Sillince describes the Mirrlees-Diesel system as applied to the propulsion of an oil-carrying vessel of 1800 tons. The propelling machinery consists of two 300-b.h.p. 250-r.p.m. six-cylinder Mirrlees-Diesel engines. There is a dynamo on each shaft, and each of these dynamos is rated for an output of 60 b.h.p. at 125 r.p.m. Each propeller shaft carries a reversible, variable-speed motor. Either of the two dynamos can drive either or both of the two motors, thus ensuring great reliability. It is pointed out that the size, weight,

and price of the electrical equipment are much less than in a system where the entire power is transmitted electrically at all speeds.

In Fig. 16 are shown rough outlines relating to an 840 shaft-h.p. cargo vessel, equipped on lines proposed by Mr. H. A. Mavor, with three Diesel oil engines and electric transmission. Mr. Mavor holds that this arrangement would be appropriate for cargo vessels for certain routes and services. He bases his calculations on a cost of £2 per ton for crude petroleum. He employs three direct-driven 400-r.p.m. generating sets, supplying alternating electricity of a periodicity of 13·3 cycles per second. Each of the three propellers is direct connected to a motor of the "spinner" type described in Chapter XIII. Mr. Mavor has given a description of this 800-ton cargo vessel at p. 246 of vol. 179 of the *Proc. Inst. Civil Engrs.* (February, 1910). He compares the weights of machinery and fuel for his design, and for an ordinary single-screw equipment driven by a 67-r.p.m. piston engine. Mr. Mavor's estimates of the weights in the two cases are as follows:—

	Mr. Mavor's design.	Direct-driven alternative.
Diesel engines and alternators	87 tons	—
Switch-gear, motors, and propellers	95 "	—
Oil fuel for 15 days at full power	88 "	—
Steam engines	—	160 tons
Boilers	—	160 "
Fuel for 15 days	—	250 "
Total weight of machinery and fuel	270 "	570 "
Ditto of machinery alone	182 "	320 "

Mr. Mavor states that the working cost in the second case at full power with coal and steam, coal being taken at 20*s.* per ton, was £17 per day; and with oil fuel at 40*s.* per ton, he gives the corresponding working cost, in the first case, to be only some £12 per day. His estimates are based on a coal consumption for the piston-engine plant of 1·9 lb. of best Welsh coal per shaft h.p.-hour, and on a fuel consumption for the Diesel-engine plant of 0·65 lb. of oil per shaft h.p.-hour. He states that although at the time of writing (1910) the price of the Diesel-engine plant would be some £3000 greater than that of the normal equipment, there is practically certain to be a reduction in the price of the Diesel-engine plant in the

immediate future, owing to expiry of patents and to reduction in the cost of manufacture. Amongst the advantages of his proposal, Mr. Mavor explains that "when it is desired to run the ship for prolonged periods at low speed, as, for instance, in navigating rivers or canals, the advantage of being able to shut down those generating units which are not required is evident. Electric transmission is the only practical means by which this desirable end may be attained. No conceivable combination of gearing would accomplish the same result. The diameter of the propeller being usually limited by the draught of the ship, it will be seen that each of the three propellers in the electrical equipment may be of the same, or nearly the same, diameter as the single propeller, and that a decided gain in efficiency may be anticipated with confidence."

In the discussion of this paper it was contended that since cargo vessels did not require to be run at other than one particular speed, the case was not appropriate for interposing electrical transmission between the engines and the propellers. But Mr. Mavor stated that "a cargo boat doing general tramp service had to run at speeds varying from 9 to 13 knots for months at a time on one trade. At one time a 9-knot speed was most economical for her purpose, and at another time 13 knots." Mr. Mavor explained that his cost estimates applied exclusively to routes where the fuel costs would be those he had employed. Since at ports in Britain the cost of coal would be very much lower, the comparison was not intended to apply to a boat sailing between such ports.

Data of "The Electric Arc" (see footnote on p. 85).

Length between perpendiculars	50 ft.
Beam	12 ft.
Depth (moulded)	7 ft. 4 in.
Draught (maximum)	4 ft. 6 in.
Builder's Estimate of Comparative Results on Lines of Ordinary Practice :—	
Engine power required	45 h.p.
Propeller speed	750 r.p.m.
Vessel speed	8 mls. p.h.
Actual Result with Electric Transmission :—	
Engine power	35 h.p.
Shaft h.p.	24·7 h.p.
Engine speed	800 r.p.m.
Propeller speed	400 r.p.m.
Mean speed on measured mile	8¼ mls. p.h.

In some tests made on May 31, 1911, it was ascertained that in 23 seconds the vessel could be completely stopped from full steam ahead. The propeller could in 13 seconds be reversed from full revolutions ahead to two-third revolutions astern.

CHAPTER XII

ALTERNATING AND CONTINUOUS ELECTRICITY FOR SHIP PROPULSION

In land applications of electrical methods to the transmission of power it has been found that in the vast majority of cases the most economic and appropriate means comprise the features of generating and transmitting the power in the form of alternating electricity, and then transforming this alternating electricity into continuous-electricity and distributing it in this latter form to continuous-electricity motors. But since on board ship the transmission is over a very short distance instead of over distances ranging from a mile or two up to a hundred miles or more, one of the chief reasons for employing alternating-electricity generating and transmitting plant is absent from the proposition. Nevertheless, there are other very important features of alternating apparatus (both generators and motors) which have sufficed, in the opinion of most engineers who have investigated the question, to justify its exclusive adoption for ship-propulsion purposes. Thus, at p. 16 of *The Electrician* for June 10, 1910, Mr. Mavor expresses the opinion: "That continuous currents are unsuitable for the purposes proposed, because of the large size of the units, generators, and motors, and because of the greater difficulty of dealing with large currents." Mr. Mavor furthermore states: "That as it is now customary on land to generate all large currents as alternating currents, the same course should be followed at sea, and there does not seem to be any adequate reason for converting to continuous current."

On p. 25 of this same issue of *The Electrician*, Mr. Durtnall, expresses the opinion that: "Owing to the vast power to be handled, the electrical propulsion of large ships will only be possible by the adoption of a polyphase-current system." Both these

engineers are developing systems of ship propulsion in which generators of polyphase electricity supply power to squirrel-cage motors. These two features also characterize a system of ship propulsion invented by Mr. J. N. Bailey and put forward by the British Westinghouse Company. This system is described in an article by Mr. H. C. Leake, at p. 19 of *The Electrician* for June 10, 1910.

While I fully agree to the proposition that good systems of electrical ship propulsion have been developed, in which alternating machinery is employed throughout, I am of opinion that insufficient attention has been given to certain attributes of electrical apparatus which—on the whole—weigh in favour of the use of continuous electricity for some classes of ships. When, some five or six years ago, the subject of the electric propulsion of ships was first given any really large amount of study, a chief factor related to obtaining the economy incident to the use of high-speed steam turbines and low-speed propellers. No satisfactory continuous-electricity generators for economical steam-turbine speeds have ever yet been produced for outputs of any magnitude, although large sums of money have been spent in endeavouring to produce such machines. Although ten years ago it was confidently and widely asserted that there was no inherent impossibility involved in the design of large continuous-electricity generators for economical steam-turbine speeds, the results achieved, even after ten years of effort, are strikingly puerile when contrasted, as in Fig. 17, with the progress which has taken place in the development of large turbo-alternators. The two curves in Fig. 17 relate to the turbo-driven generators of one of the very largest electrical manufacturing firms in the world. This firm, after spending several years in endeavouring to develop extra-high-speed continuous-electricity sets, has finally accepted the inevitable and has standardized its continuous-electricity turbo-driven generators with the low speeds for various outputs set forth in the full-line curve of Fig. 17. This curve should be contrasted with the dotted-line curve in the same figure. This dotted-line curve represents the same concern's line of standard alternating-electricity, 50-cycle, turbo-generators. Various firms in this country are still representing that they can build thoroughly satisfactory continuous-electricity sets of large output, and for steam-turbine speeds. But from a glance at the curves in Fig. 17, it is very evident that the

concern in question, at any rate, prefers to employ special steam turbines running at less than half the speed which would be preferred for the steam turbine, and it adopts these low speeds as a wise concession to the inherent inadaptability of the continuous-electricity generator of large output, to operation at economical steam-turbine speeds. This is the upshot of earnest attempts, covering some 10 years, to produce continuous-electricity generators of really large capacity, suitable to give satisfactory results at economical steam-turbine speeds. A considerable proportion of the machines of this type which have been turned out during the last eight years, and

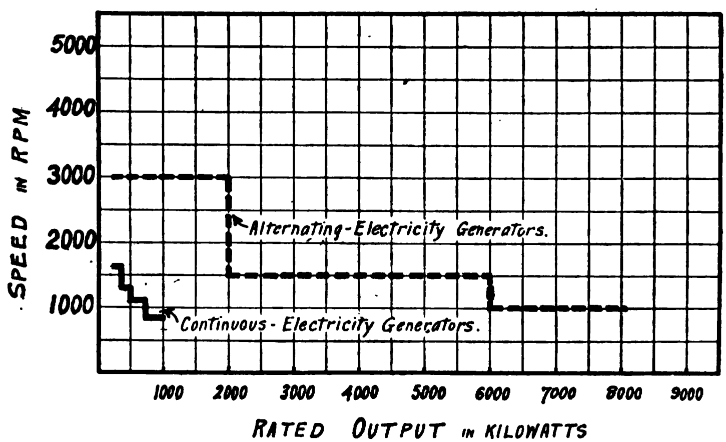


FIG. 17.—Curves showing the Rated Speeds of Alternating- and Continuous-Electricity Generators for various Rated Outputs, as built by a large firm of manufacturers of electrical machinery.

amongst them several which were heralded as complete successes, have already been consigned to the scrap heap. Steam turbines constitute excellent prime movers for alternators of from 2000 kw. to 20,000 kw. output, but slow-speed or moderate-speed engines no less certainly constitute much more appropriate prime movers for direct connection to continuous-electricity generators.

The last few years have, however, seen the development of 98-per-cent.-efficiency double-helical speed-reduction gearing. More than one reliable firm[1] is prepared to undertake the supply of highly

[1] André Citroën & Co., of 19, Queen Victoria Street, London, E.C.; the Power Plant Co., Ltd., West Drayton, Middlesex, England; the Westinghouse Machine Co., Pittsburg, Pennsylvania, U.S.A.; Messrs. D. Brown of Huddersfield, England.

efficient double-helical gearing for transmitting thousands of horse-power. Thus the use of moderate-speed continuous-electricity generators, driven through mechanical gearing from high-speed steam turbines, has now become a sound engineering proposition.

Moreover, as we have seen, there has been a gradual development of view as to the extent of the advantages to be gained by electric propulsion, and it is now seen that the obtaining of high load factor and facility of reversal, together with manœuvring power, are often the considerations of leading importance. This has turned the attention of engineers to the possibilities of securing the low fuel cost associated with the employment of internal-combustion engines. These engines are usually built for obtaining maximum economy at

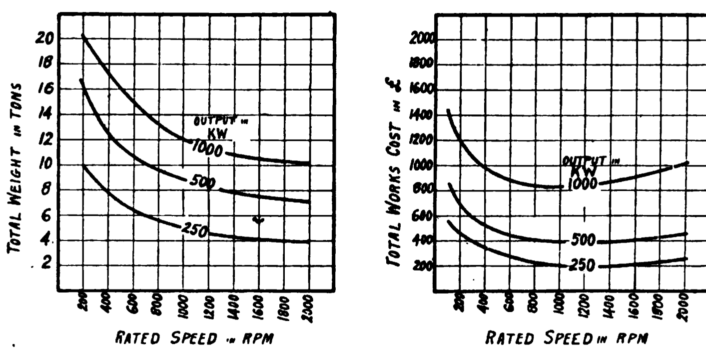


Fig. 18.—Total Weights and Total Works Costs of 500-volt Continuous-Electricity Generators.

distinctly moderate or even low speeds of revolution, and are thus, so far as relates to speed, ideal prime movers for direct connection to continuous-electricity generators. So far, then, as relates to the *generator* portion of the electrical machinery, the former non-eligibility of continuous electricity no longer exists.

But continuous-electricity generators are, for a given speed, more expensive than alternating-electricity generators, and it would be inadvisable to employ them unless fully compensating advantages are thereby attained. The curves in Fig. 18 are plotted from rough but representative values of the total weight and total works cost of continuous electricity generators of 250 kw., 500 kw., and 1000 kw. rated capacity. Since these data are based on ratings corresponding

to land practice, where it is customary to require sustained overload capacities of, say, 50 per cent., it will be right to increase these ratings by some 25 per cent. when employing equivalent plant for marine propulsion. For in marine propulsion the plant is proportioned for the ship's maximum speed on trial runs, and this in itself constitutes an appropriate overload test.

So if we increase the ratings set against the curves in Fig. 18, to 312 kw., 625 kw., and 1250 kw., the maximum loads required of the machines will be conservatively within their capacity. The curves show that, beyond very moderate speeds, the weight only decreases very slowly with increasing speeds, and that the total works cost is actually greater at high speeds than at intermediate speeds. It should hardly be necessary to remind the reader that the price which must be paid for such machinery is greatly in excess of the total works cost, which merely represents the costs entailed at the works. The cost of marketing the product is considerable, and few concerns could make any profit in selling such machinery at a price much less than 50 per cent. in excess of their total works cost.

The curves in Fig. 19 relate to 1500-kw. continuous-electricity and alternating-electricity generators, and the ratings are those corresponding to land practice. These are average curves for machines manufactured under similar conditions and built to reasonable specifications. It is seen that for the range of speeds corresponding to steam-turbine drive, the continuous-electricity generators cost, per kw., from 20 per cent. to 40 per cent. more than the alternating-electricity generators of the same output. Moreover the continuous-electricity machines will at these speeds be mechanically and electrically very much inferior to alternators. With higher ratings than 1500 kw. the cost per kw. is, for alternating machines, very appreciably less per kw. than the values given by the curve in Fig. 19. Thus, whereas the lowest value shown by this curve is some 13*s.* per kw., the total works cost per kw. for a 6000-kw. alternator at its most economical speed is only about 10*s.* per kw. Fifteen-hundred-kw. *continuous*-electricity generators are, however, most unsatisfactory machines when designed for speeds much above, say, 500 r.p.m., whereas *alternators* of this capacity actually have better characteristics with increasing speed up to fully 1500 r.p.m. Consequently the resultant advantage at high speeds is made up of a

combination of the considerable difference in cost and the considerable difference in quality, and is much greater than would be inferred from a hasty study of the curves in Fig. 19. It would be putting the case more plainly to describe the lines of turbo-driven continuous-electricity generators now on the market as generators for direct connection to *low-speed* steam turbines. These low-speed

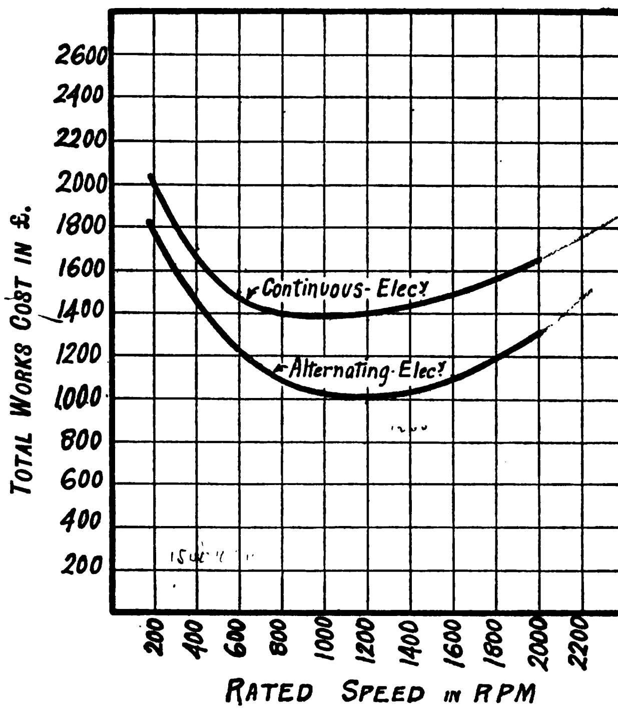


FIG. 19.—Curves showing Total Works Costs of Continuous- and Alternating-Electricity Generators for a Rated Output of 1500 kw. and designed for various Speeds.

steam turbines necessarily have a greater appetite for steam than the higher-speed steam turbines employed for driving alternators of the same rated output. The largest turbo-driven continuous-electricity sets (say 1000 kw.) have a distinctly greater steam-consumption per kw.-hour of output than is the case with turbo-driven alternators of the same rated output but double the speed. While efforts to improve the continuous-electricity direct-connected turbo-generator are to be commended, there is nothing to be gained in the long run

by representing it as being other than a most unsatisfactory machine.

I have set forth in very plain language the disqualifications of the direct-connected turbo-driven continuous-electricity generator in order that my advocacy of the advantages of employing continuous electricity in certain cases for ship propulsion shall be utterly dissociated from any advocacy of direct-connected turbo-driven continuous-electricity sets. Where the prime movers are steam turbines, I advocate the interposition of mechanical speed-reduction gearing between the turbine and the continuous-electricity generator. For the much lower speeds appropriate to internal-combustion engines, I advocate their direct connection to the continuous-electricity generators. Each of these will in many cases constitute commercial and economical combinations.

Why should it, for ship propulsion, be so desirable to employ continuous electricity? The reason is that efficient and effective speed control and high starting torque are more pre-eminently inherent to continuous motors than to alternating motors. We shall examine various systems in which the inherent inferiority of alternating motors is more or less effectively overcome, but I am of opinion that to ensure to electric propulsion the important feature of increased manœuvring power, the employment of continuous-electricity motors is very desirable. With such motors it is absolutely certain that a ship can be stopped and reversed in a shorter distance than when the propellers are directly driven from the engines. But the advocates of the use of alternating motors will assert that continuous-electricity motors are larger and more expensive than alternating-electricity motors. For certain speeds and ratings, continuous-electricity motors *are* at a considerable disadvantage in this respect, but not for the slow speeds appropriate for driving a ship's propellers. Polyphase motors are essentially adapted to high-speed work, and continuous motors to low-speed work.

In Fig. 20 are shown two 150-h.p. continuous and two 150-h.p. induction alternating motors. The motors at the left are designed for the low speed of 68 r.p.m. and the motors at the right are for a nine-times-greater speed, namely 612 r.p.m. It is seen that while for 68 r.p.m. the polyphase alternating motor has a 50 per cent. larger

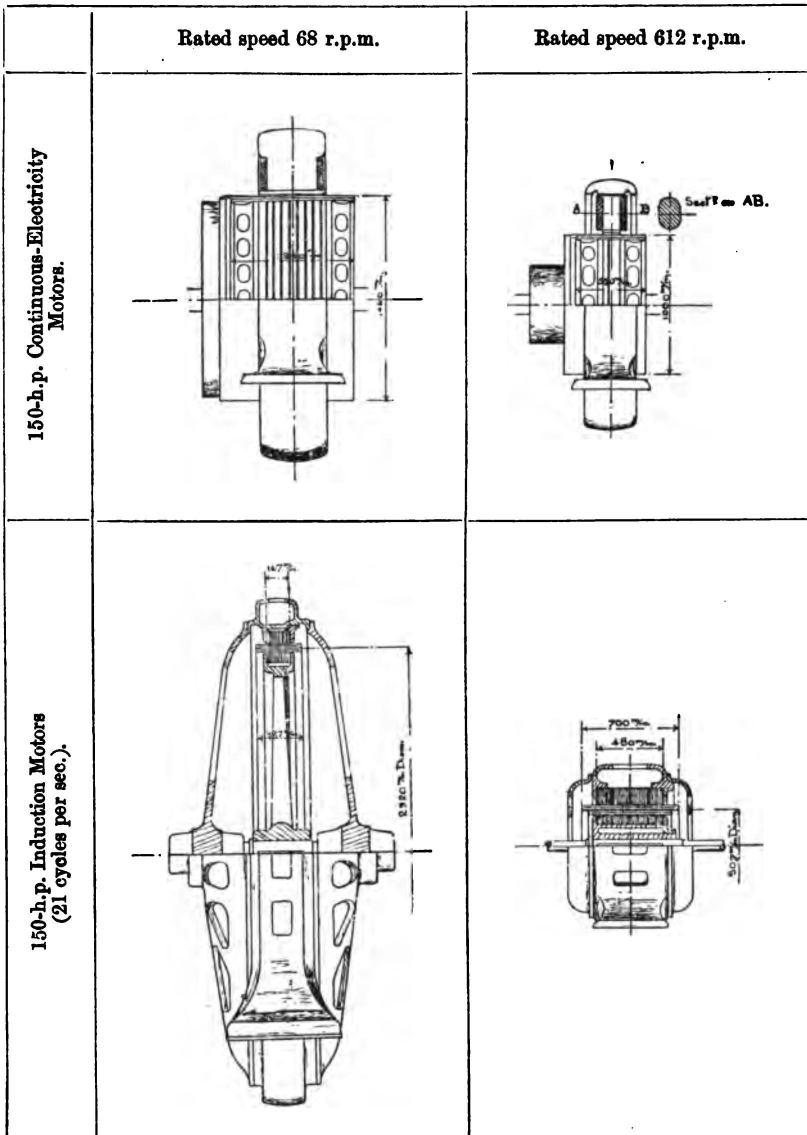


FIG. 20.—Continuous- and Alternating-Electricity Motors for 150-h.p. and designed for Low- and High-Speed Ratings.

overall diameter, for 612 r.p.m., the continuous motor has a 50 per cent. larger overall diameter. These proportions are inherent to the types and are not optional to the designer. Indeed, so far as the designer can control the proportions, it is the continuous motor which is most flexible as regards the possibility of decreasing the diameter for a given speed. A low-speed polyphase motor *must* have a relatively very large diameter. Not only is the size of a low-speed polyphase motor disproportionately large, but this is also the case with its weight and cost. The weights and total works costs of the four 150-h.p. motors shown in Fig. 20, are set forth in the following table :—

	Total Works Cost.		Total Weight.	
	Rated speed.		Rated speed.	
	68 r.p.m.	612 r.p.m.	68 r.p.m.	612 r.p.m.
Continuous-electricity motor . .	£500	£180	10 tons	3·0 tons
Induction motor	£550	£110	14 „	1·8 „

Nor does this exhaust the comparison. While the properties of polyphase alternating motors improve with *increasing* rated speed, with continuous motors the reverse is the case, and their properties improve with *decreasing* rated speed. Thus let us examine the efficiencies in the following table :—

	Efficiency at full load.		Efficiency at half load.	
	68 r.p.m.	612 r.p.m.	68 r.p.m.	612 r.p.m.
Continuous . . .	89 per cent.	88 per cent.	87 per cent.	83 per cent.
Polyphase . . .	86 „	90 „	86 „	90 „

The power factors for the polyphase motors at full and half load are shown below :—

	68 r.p.m.	612 r.p.m.
Power factor at full load . .	0·86	0·91
„ „ half load . .	0·76	0·86

For the continuous motors the reactance voltages of the two designs are—

68 r.p.m.	1·3 volts
612 r.p.m.	2·4 volts

A study of these various results fully bears out the proposition of the inherent appropriateness of continuous-electricity motors for low

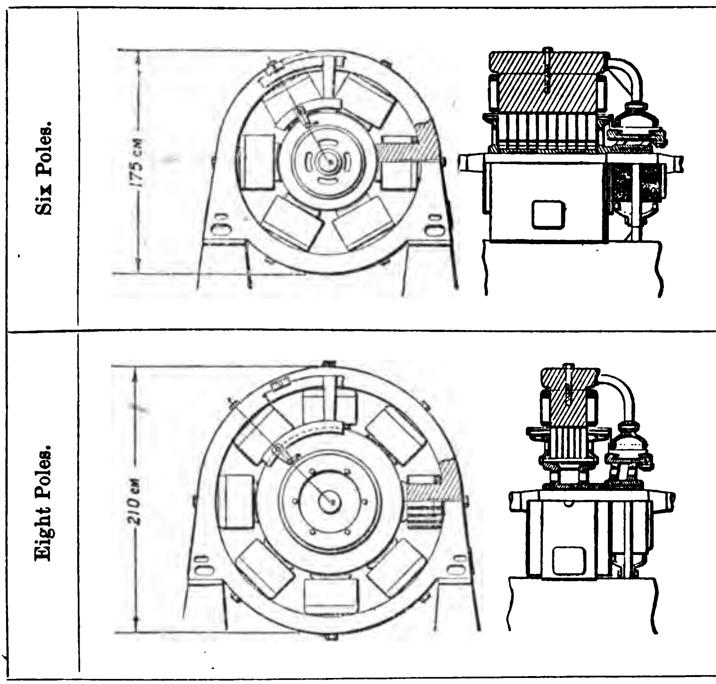


FIG. 21.—Six-Pole and Eight-Pole Designs for 300-h.p. 250-r.p.m. Continuous-Electricity Motors.

speeds and alternating-electricity motors for high speeds. While no single attribute is of supreme importance in arriving at this conclusion, the aggregate result of the various component properties permits of no escape from the conclusion.

So far as concerns ship propulsion, one of the more important features of a low-speed continuous-electricity motor is that the diameter of the ideal design is so very much less than that of the

polyphase motor for the same output and speed. Moreover, as already indicated, the designer can, to a certain extent, control the diameter of a continuous-electricity motor, and make it still smaller than in the ideal design, by sacrificing to a slight extent the full measure of good quality in other respects.

Thus in Fig. 21 are shown two 300-h.p. 250-r.p.m. 250-volt continuous-electricity motors. The one is designed with six poles and the other with eight poles, and while both are fairly good designs, the former has a very appreciably smaller diameter and is consequently more appropriate where space is limited. The two designs in Fig. 22 both relate to 130-h.p. 400-r.p.m. 500-volt continuous-electricity motors. Finally there are shown in Fig. 23, two alternative designs for 35-h.p. 600-r.p.m. 220-volt continuous-electricity motors. It will be seen that in each case the right-hand design has a very materially larger overall diameter than the left-hand design.

With slow-speed polyphase alternating motors, on the contrary, this is not the case. The smallest diameter consistent with a sound design of only moderately-good properties is already large, and an increase in this least practicable diameter is attended with but a slow improvement in the properties of the motor. In the following table are given the values of the maximum power factor for five alternative designs for a 75-h.p. 8-pole, 630-r.p.m. 42-cycle,

Airgap diameter (in cm.).	Overall diameter (in cm.).	Maximum power factor.	Total works cost (in shillings).
43	60	0.87	1550
58	80	0·89	1480
74	95	0·91	1610
89	110	0·92	1900
104	125	0.92	2300

350-volt squirrel-cage induction motor. Each successive design has a larger overall diameter, and although this is accompanied by an increased total works cost, there is a gradual improvement in the maximum power factor, which is very unsatisfactory in the designs of small diameter, but which rises to the value of 0·92 when the larger diameters are employed. The data in the above table is taken from p. 598 of the 2nd edition of the author's "Electric Motors" (Whittaker & Co., London, 1910).

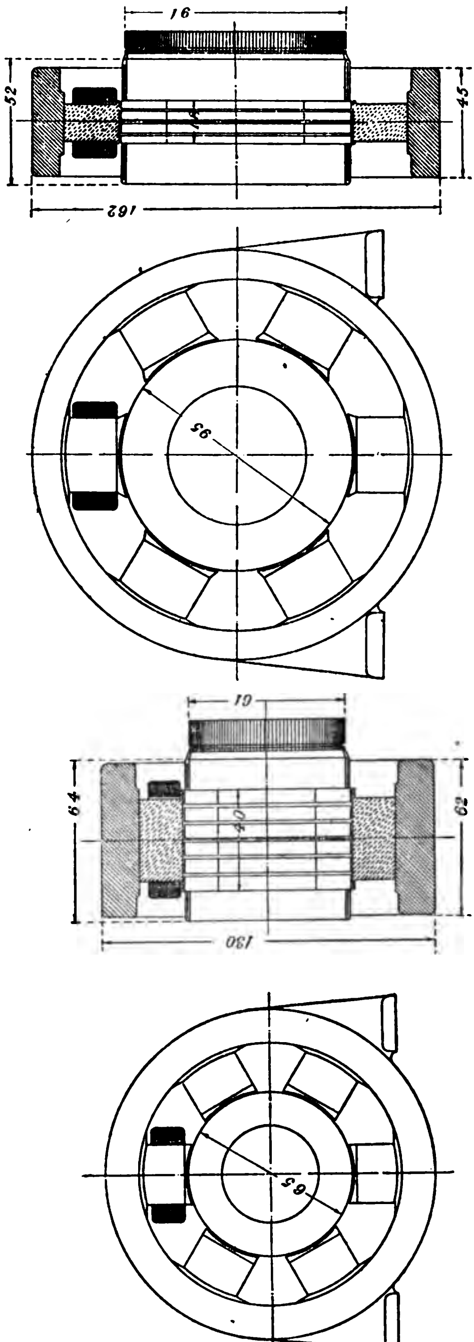


FIG. 22.—Two Alternative Designs for a 130-h.p. 400-r.p.m. 500-Volt Continuous-Electricity Motor. All dimensions in cm.

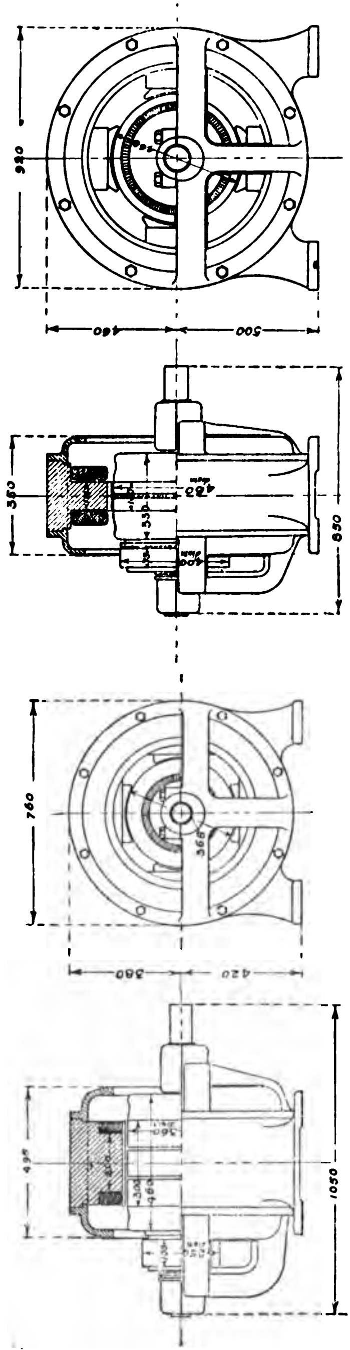


FIG. 23.—Two Alternative Designs for a 35-h.p. 600-r.p.m. 220-Volt Continuous-Electricity Motor. All dimensions in mm.

In the following table are given some rough leading dimensions of designs for 1000-h.p. 25-cycle induction motors for five different speeds:—

Speed in r.p.m.	125	250	375	500	750
Number of poles	24	12	8	6	4
External diameter of rotor. . .	238 cm.	180 cm.	138 cm.	114 cm.	87 cm.
Gross length of rotor core . . .	53 cm.	66 cm.	76 cm.	83 cm.	95 cm.
Maximum power factor. . . .	0·930	0·940	0·950	0·955	0·960
Total works cost	£1000	£760	£640	£570	£500

Here, again, we see that the diameter is very large for the low-speed designs, and that the power factor decreases with decreasing rated speed.

It has been claimed that the polyphase motor has a great advantage for ship propulsion, in that it can be built in very large units. Some rough leading dimensions for 100-h.p., 1000-h.p., and 10,000-h.p. 25-cycle, 125-r.p.m. 24-pole squirrel-cage induction motors are given in the following table:—

Rated output.	100 h.p.	1,000 h.p.	10,000 h.p.
External diameter of rotor . .	151 cm.	288 cm.	565 cm.
Gross core length	28 cm.	53 cm.	104 cm.
Maximum power-factor . . .	0·90	0·93	0·91
Peripheral speed in m.p.s. . .	9·8	18·8	37·0
Total works cost	£190	£1,000	£4,200
Ditto per h.p.	£1·9	£1·09	£0·42

In the case of large ships, the driving of a single propeller shaft may require several thousand h.p. when the ship is travelling at its highest speed. But we have seen that the power required is proportional to the cube of the speed. Consequently at eight-tenths of full speed, only half as much power is required as at full speed. For vessels which travel for any considerable proportion of their time at even so slight a decrease in speed as 20 per cent. less than full speed, it is in the interests of efficiency to have at least two motors on each shaft. This permits of running at eight-tenths speed with only half the motors in circuit, and with these motors operating at their rated load and hence at good efficiency. At *half*-speed the power required is of the order of only *one-eighth* of that required at full speed.

Consequently for vessels which for any considerable percentage of the time proceed at *half*-speed, a still further subdivision of the motors is desirable. Such subdivision of the motors has the additional advantage that the smaller motors are of smaller external diameter, and conform better to the space available for them. On the other hand, the greater the subdivision into component machines the higher the price per h.p. Also the efficiency is slightly lower in small than in large motors.

In the following table are given rough values for the estimated complete weight, in tons, of some designs for large 33-cycle squirrel-cage induction motors for a synchronous speed of 124 r.p.m. :—

Rated output.	Complete weight exclusive of shaft and bearings.
1,000 h.p.	15 tons
2,000 „	25 „
3,000 „	34 „
4·000 „	42 „
5,000 „	50 „

The total works cost would range from 12*s.* per h.p. for the 1000-h.p. motor down to some 8*s.* per h.p. for the 5000-h.p. motor. This corresponds to some £40 per ton. The efficiencies, exclusive of friction, are of the order of from some 94·5 per cent. for the 1000-h.p. motor, up to some 96 per cent. for the 5000-h.p. motor. The power factors at full load, in the two extreme cases, are of the order of 0·91 and 0·93 respectively. The external diameter of the 1000-h.p. motor is some 3·4 metres, and that of the 5000-h.p. motor is a matter of 5 metres.

The disabilities of low-speed induction motors may be escaped, and advantage may be taken of their good qualities by arranging that high-speed motors shall drive the propeller-shafts at low speeds through double-helical speed-reduction gearing. The pinions of two (or even more) motors could be arranged to engage with a single low-speed gear-wheel on the propeller shaft, quite analogously to the way in which two steam turbines drove the *Vespasian's* shaft in the tests made by Parsons, and already described on p. 49. Usually the 2 per cent. loss in the gearing would be largely offset by the higher efficiency of the high-speed induction motor, and the weight

and cost of the gearing would be partly offset by the lesser weight and cost of high-speed as compared with low-speed induction motors. The difficulties associated with finding space for large diameters are also eliminated in ships by this plan.

Cascade-Control of Motors

There is a method of operating polyphase induction motors in pairs coupled to the same shaft, which permits of obtaining a given aggregate output with a smaller external diameter than is practicable when only one ordinary motor is employed. According to this method, the current induced in the secondary element of the first motor is led to the primary element of the second motor and the secondary element of the second motor may either be short-circuited or else it may include external resistances. In the latter case, the motors can exert a high torque at starting. If both motors have, say, 6 poles, and if, for example, the periodicity of the supply circuit is 50 cycles per second, then the shaft will be driven at a speed of only 500 r.p.m., whereas an ordinary 50-cycle 6-pole induction motor has a speed of 1000 r.p.m. Similarly the first motor may have 8 poles and the second motor 4 poles, and the speed will also in this instance be 500 r.p.m. In other words, the speed of the shaft will be that at which it would be driven by a motor with a number of poles equal to the sum of the numbers of poles on the two component motors. In this way, not only can the external diameter be decreased, but there is the further advantage that the shaft may be driven at more than one speed. Thus if both 50-cycle motors have six poles, then when they are connected in cascade, they drive the shaft at a speed of only 500 r.p.m.; but when they are both in parallel on the supply circuit, they drive the shaft at 1000 r.p.m. If one of the component motors has 8 poles and the other 4 poles, then three speeds may be obtained. When connected in cascade, the speed is that of an $(8 + 4 =)$ 12-pole motor, *i.e.* (on a 50-cycle circuit), 500 r.p.m. If the 8-pole motor is alone in circuit, it runs at 750 r.p.m.; and the 4-pole motor, when alone in circuit, runs at 1500 r.p.m. But when connected in cascade (*i.e.* for the lowest speed), the power factor is very poor, for the reason that the magnetizing current of the second motor is, in the first motor, superposed on the first motor's own

magnetizing current. Such a combination is, as compared with an ordinary motor, characterized by poor power factor, low efficiency, relatively small capacity for overloads, and increased heating.

The Cascade Motor

Mr. L. J. Hunt, of the Sandycroft Foundry Co., has devised a very ingenious motor which may be crudely, but appropriately, described as consisting of the windings of two cascade-connected motors superposed on a single stator and rotor core. Certain very considerable advantages appear to have been obtained by these means. Chief amongst these is that, to obtain the low speed corresponding to an ordinary 12-pole motor, the stator of a Hunt cascade motor is provided with an 8-pole winding. This permits of employing a smaller diameter, or of improving the power factor, or the advantage may be divided between these two features. On a 50-cycle circuit, a Hunt motor, with an 8-pole stator winding, runs at only 500 r.p.m., whereas an ordinary 8-pole motor would run at 750 r.p.m. This means of obtaining relatively low speeds in induction motors, or alternatively, of improving the results at low speeds, is of particular interest in connection with the question of ship propulsion by electric motors for the reasons already discussed in this and earlier chapters. Furthermore, a Hunt motor may be operated at more than one speed. The most usual plan adopted for variable speed by these means is to arrange the motor for two speeds with a ratio of 2 : 3. Thus the lowest speed of a motor with a 16-pole winding on the stator of a Hunt cascade motor is (at 50 cycles) 250 r.p.m., but when reconnected as an ordinary motor, it runs at 375 r.p.m. The switch connections for obtaining either of these two speeds are very simple, and the ratio of 2:3 is decidedly appropriate for ship propulsion. A further advantage, restricted, however, to the single-speed motor, is that while in order to obtain good starting torque with an ordinary motor, resort must be made to slip rings, in the Hunt cascade motor the starting resistances are inserted in circuits connected to the stator winding, thus avoiding all sliding contacts.

Certain properties relating to overlapping of magnetic fields in the way in which they are employed in the Hunt motor, result in a

very uniform torque at dead-slow speeds, and if this attribute should prove to be present in the very large size of motors which would often be required in ship propulsion, it would be a very useful factor in manœuvring and in astern running. The cascade motor has been described by Mr. Hunt in the *Proc. Inst. Elec. Engs.* for March 19, 1907.

CHAPTER XIII

SOME SYSTEMS OF PROPELLING SHIPS ELECTRICALLY

In British patent No. 11,183 of 1907, Mr. Henry A. Mavor describes a system of ship propulsion in which a wide range of speeds is efficiently obtained with squirrel-cage induction motors. The invention will be understood by describing its application to a case where a propeller shaft carries four driving motors. These four motors are designated in Fig. 24 as E, F, G, and H. They are wound

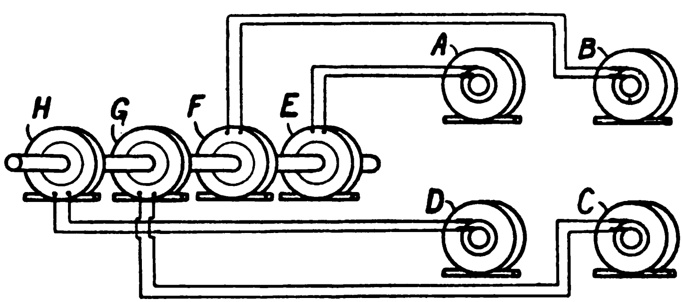


Fig. 24.—Alter-Cycle Control of Induction Motors.

respectively for 24, 36, 48, and 72 poles. As of interest to engineers who may not as yet have acquainted themselves with the fundamental principles of electricity, I give a table on opposite page in which are set forth the speeds at which motors of various pole-numbers will run when supplied from circuits of the periodicities set forth at the heads of the vertical columns in the table.

The motors only run at the above speeds when unloaded. When carrying full load the speed decreases by one or two per cent. (*i.e.* by an amount proportional to the "slip"), but for the purposes of the present explanation we may neglect the "slip," and consider that the

Number of poles.	Speeds in r.p.m. for frequencies of—				
	25 ~	33 ~	40 ~	50 ~	60 ~
2	1,500	2,000	2,400	3,000	3,600
4	750	1,000	1,200	1,500	1,800
6	500	667	800	1,000	1,200
8	375	500	600	750	900
10	300	400	480	600	720
12	250	330	400	500	600
14	214	286	343	428	515
16	183	250	300	375	450
18	167	222	267	333	400
20	150	200	240	300	360
22	137	182	218	273	327
24	125	167	200	250	300
26	116	154	185	231	277
28	107	143	172	214	257
30	100	133	160	200	240
32	93·8	125	150	188	225
36	83·3	111	133	167	200
40	75·0	100	120	150	180
44	68·2	90·9	109	136	163
48	62·5	83·3	100	125	150
52	57·7	76·9	92·3	115	138
56	52·5	71·5	85·9	107	129
60	50·0	66·7	80·0	100	120
64	46·9	62·5	75·0	93·8	113
68	44·1	58·7	70·6	88·1	106
72	41·7	55·5	66·7	83·3	100

motors run at the precise speeds indicated in the above table. These speeds are called the "synchronous" speeds. Let us consider that in a certain case the maximum speed required of the propeller shaft is 100 r.p.m. At this speed we shall require the full power of all four motors. From the table we readily deduce (by proportion) the result that to run a 24-pole motor at 100 r.p.m. the periodicity of the supply must be 20 cycles per second. Making a similar determination of the periodicities required to drive each of the motors at 100 r.p.m., we arrive at the following results:—

Designation of motor.	Number of poles.	Required speed.	Required periodicity of the supply.
E	24	100 r.p.m.	20 cycles per sec.
F	36	100 "	30 " "
G	48	100 "	40 " "
H	72	100 "	60 " "

Thus, at the highest speed and the maximum power, we shall require to provide four different sources of electricity, each source being characterized by its periodicity. The periodicities of these four sources, which are the generators A, B, C, and D of Fig. 24, must be respectively 20, 30, 40, and 60. If these periodicities are to be supplied from 600-r.p.m. engine-driven generators, the numbers of poles of these generators will be found (from the table on p. 111) to be those shown in the last column of the following table:—

Designation of generator.	Speed.	Required periodicity.	Number of poles.
A	600 r.p.m.	20 cycles per sec.	4
B	600 "	30 " "	6
C	600 "	40 " "	8
D	600 "	60 " "	12

At first sight, the reader may not divine the reason for supplying these four motors from generators of four different periodicities. Why not have built each of the motors with 24 poles, and each of the generators with 4 poles? Then, with all our plant in operation, we could have driven the ship at its maximum speed. But how could we have driven the ship at, say, two-thirds speed? We should have required to drive the propeller at ($\frac{2}{3} \times 100 =$) 66·7 r.p.m. This is simply and efficiently accomplished by connecting motors F and H to generators A and C, which provide respectively two-thirds of the periodicity of the generators B and D, to which F and H were connected for top-speed running. For this lower speed only—

$$(0{\cdot}667^3 =)\, 0{\cdot}3$$

or three-tenths as much power is required as at top-speed, and half the motors and generators will be ample to provide this smaller amount of power. Consequently, generators B and D and motors E and G are shut down until the highest speed is again required. The electrical plant in circuit is thus always carrying a large percentage of its rated load, and is consequently always operating at high efficiency and power factor.

When it is required to run at only half speed, the power necessary is of the order of only one-eighth, and a single motor is more than sufficient. This can be provided by operating motor H from generator

B, or motor G from generator A. One-third speed is obtained by operating motor H from generator A.

The invention has been described for the simple case where all four motors drive a single shaft, but obviously the motors may be distributed amongst more than one shaft. Moreover, the principle is not limited to any particular number of motors or generators. In applying the principle it would sometimes be desirable to have the motors of different capacities, as also the generating sets. But each case must be specially studied in the light of a full knowledge of the results required. The system is eminently adapted to obtaining a good load factor, not only for the generators, but also for the motors. As already explained in earlier chapters, the ability to maintain a high load factor is one of the most important features which may be provided when electrical transmission is employed in ship propulsion.

The Multiple Motor

In a subsequent British patent (No. 12917 of 1909), Mr. Mavor combines in a single motor two or more motors of different pole

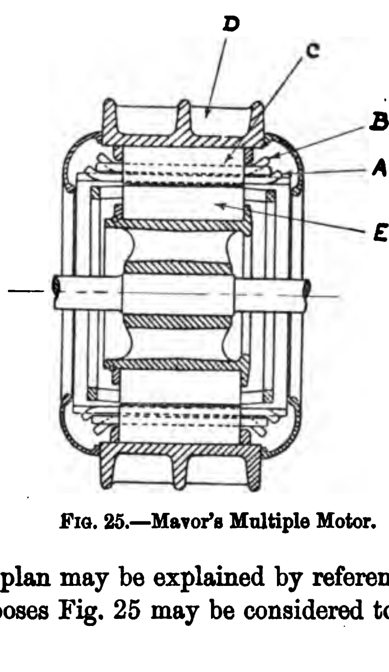


FIG. 25.—Mavor's Multiple Motor.

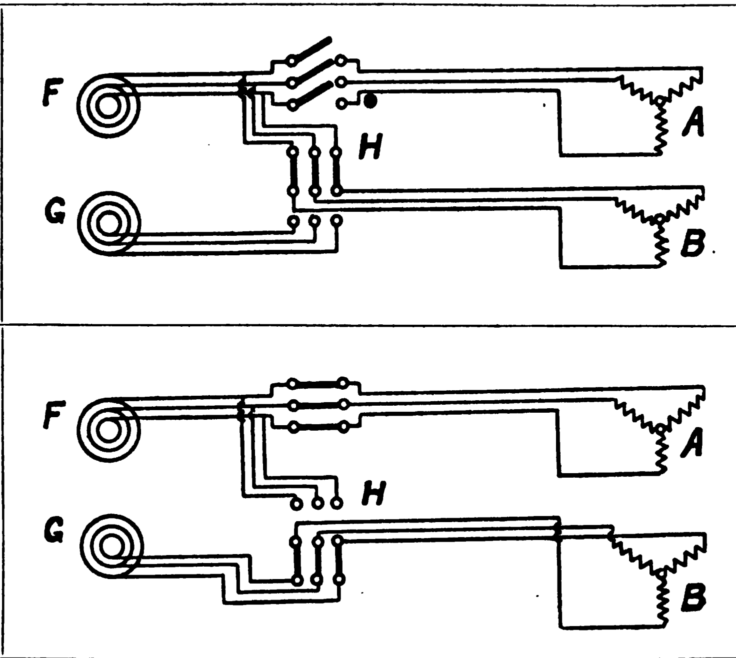
numbers. The plan may be explained by reference to Fig. 25. For descriptive purposes Fig. 25 may be considered to represent a central

longitudinal section of a multiple motor with a squirrel-cage rotor, E. A and B represent respectively 4 and 6-pole windings located in the stator core C, which in turn is built into the stator frame in the customary manner.

In Figs. 26 and 27, F and G represent two generators, the former providing a periodicity of 20 cycles per second, and the latter a

Fig. 26—(400 r.p.m.)

Fig. 27—(600 r.p.m.)



Figs. 26, 27.—Connections of the Multiple Motor for Speeds of 400 r.p.m. and 600 r.p.m.

periodicity of 30 cycles per second. In Fig. 26, the 20-cycle generator supplies the 6-pole winding B through the switch H; the 30-cycle generator G, and the 4-pole winding A, not being used. From the table on p. 111 we see that the motor will now run at a speed of 400 r.p.m. If we want to increase the speed to 600 r.p.m. we shall require—

$$\left[\left(\tfrac{600}{400}\right)^3 = \right] 3{\cdot}4 \text{ times,}$$

the amount of power required at the lower speed. Consequently, we shall desire to make effective use of our entire plant. This is

accomplished by the connections shown in Fig. 27, in which the 4-pole winding, A, is supplied by the 20-cycle circuit, and the 6-pole winding, B, by the 30-cycle circuit.

An attractive feature of this multiple-motor system is that it is unnecessary to synchronize the generators supplying the different windings. Thus in the case where the ship is proceeding at low speed, a single winding and a single generator would be employed. If the signal were given to increase the speed, the second generating set would be run up to approximately the correct speed, and the controller would be thrown over to the combination where the winding with the small number of poles is connected to the generator of low periodicity, and the winding with the greater number of poles to the generator of the higher periodicity. Then the two engines would, at leisure, be regulated until the ammeters in the two circuits indicated the correct subdivision of the load. It will be observed that the windings will often be proportioned for different loads, and that the generators will often be of different capacities. There may be more than two windings on the motor, and there may be such a multiple motor on each of several shafts, or there may be more than one multiple motor on each shaft. Such systems as those which I have described above may appropriately be termed "alter-frequency" systems. Mr. Mavor is at present testing the multiple motor in a vessel built by Messrs. McLaren Brothers, of Dumbarton. Various particulars of this boat are given on pp. 85 and 91.

The Spinner Motor

In some of Mr. Mavor's ship-propulsion designs he proposes to employ a "spinner" motor. This invention of Mr. Mavor's consists in an induction motor in which the member carrying the primary winding, as well as that carrying the secondary winding, are so mounted as to be capable of rotation. At starting, that member which is not connected to the load is allowed to rotate. As there is no torque opposing this rotation, the power required is only that necessary to accelerate the moving parts and to overcome friction. When this member has reached normal speed, a brake is applied and while it is gradually brought to rest, the rotation is taken up by the other member and by the load, which gradually accelerates as the

speed of the other member decreases. In this way, a motor with a low-resistance squirrel-cage rotor can be started against a large torque without taking an excessive current. In the "three-speed" type of spinner motor, the member which is not connected to the load but is free to rotate, is itself controlled by a second induction motor arranged to run at a speed differing from that of the first.

In Fig. 28, A represents a squirrel-cage rotor coupled to the load;

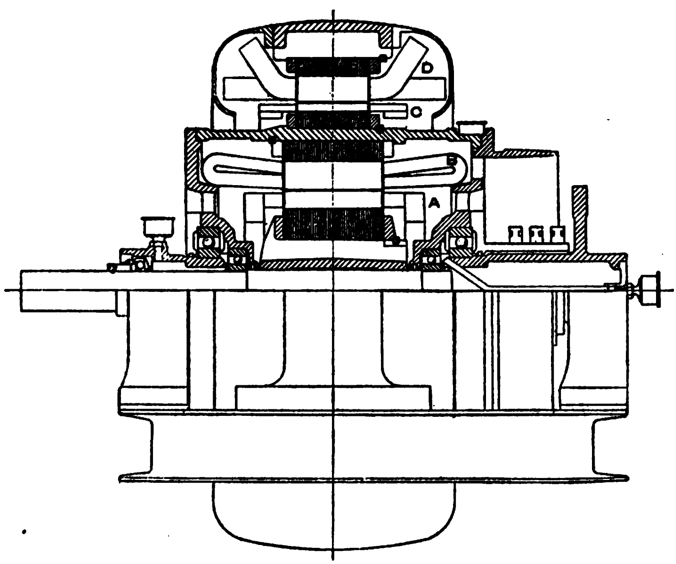


FIG. 28.—Three-Speed Spinner Motor.

the primary is shown on the "spinner" member, at B, and is mechanically attached to another squirrel-cage winding, C, at the outer periphery of the spinner. The outer member is stationary, and carries a second primary winding, D. If desired, the primary and secondary windings may be interchanged; thus the outer surface of the spinner might carry a primary winding, and the inner periphery of the stator might carry a secondary winding. If R be the synchronous speed between A and B, and R′ that between C and D, it is obvious that if the two primaries are connected to the mains, so as to cause rotation in the same direction, then, neglecting slips, the speed of the rotor will be (R + R′). If the member carrying B and C be held stationary, the speed will be R, and if the connections to

D be reversed, so as to occasion rotation in opposite directions, the speed will be (R – R′). Three speeds are thus available, and by reversing the connections to BA, the same three speeds may be obtained in the reverse direction. The electricity is delivered from an outside source to the primary windings of the stator and spinner respectively, passing in each case through a simple reversing switch which determines the direction of rotation. The stator circuit also supplies a magnet which, when no current is passing, releases a brake which brings the spinner to rest and keeps it at rest. When current is passing, the magnet lifts the brake and leaves the spinner free to revolve.

The spinner motor has been described and discussed by Mr. Mavor in a paper entitled, "Electric Propulsion of Ships, with Note on Screw Propellers," read before the Institute of Engineers and Shipbuilders in Scotland, on February 18, 1908. In addition to the preceding description, which I have chiefly abstracted from that paper, Mr. Mavor explains the method of speed control as follows:—

"The three-speed motor provides a means of obtaining all the speed variations which are required on a ship. The intermediate speeds between the three normal speeds of the motor are obtained by variations in the speed of the generating plant, which are within the limits of practicability and economy. Each propeller shaft is provided with a directly-connected motor, on which there is co-axially superimposed a second motor for speed regulation. The regulating motor is so mechanically connected and magnetically entrained with the first that the following speed variations may be effected:—

"I. For slow speed, by running the regulating motor in the reverse direction to the direct-connected motor.

"II. For intermediate speed, by running the direct-connected motor alone, the regulating motor being stopped.

"III. For full speed, by running the regulating motor in the same direction as the direct-connected motor."

In this paper Mr. Mavor suggests, for illustrative purposes, the case of a ship providing 17,000 h.p. on three propellers at the maximum speed of 21 knots. He provides this power by two turbo-driven generators. One of these has a capacity for 10,000 h.p. and the other for 700 h.p. At full speed, the 10,000-h.p. generator directly drives the direct-connected motors, and the 7000-h.p.

generator drives the regulating motors. For the lower speed of 18 knots, it is only required to run the 10,000-h.p. generating set. Thus, the coal consumption per b.h.p.-hr. is as low at 18 knots as at 21 knots. For still lower speeds, the 10,000-h.p. generating set is shut down, and the 7000-h.p. generating set is put in service. Mr. Mavor points out that "the electrical arrangements provide a means of approximating, at all working speeds of the ship, to the economy attainable on the trial trip at full speed.

Fig. 29 is an outline sketch for a 5400-b.h.p. 140-r.p.m. three-

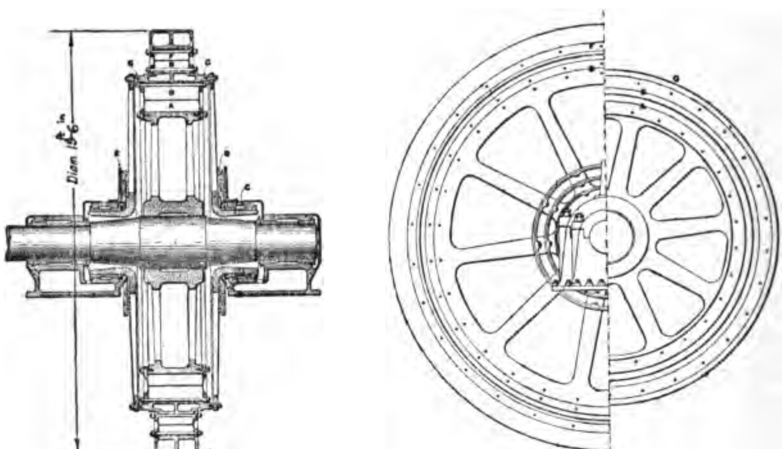


FIG. 29.—Three-Speed 5400-h.p. Spinner Motor.

speed spinner motor. This is from Mr. Mavor's paper on "Marine Propulsion by Electric Motors," read at the Institution of Civil Engineers, on December 7, 1909 (see p. 134 of vol. 179 of the *Proc. I.C.E.*). In this figure, A is the rotor, B the spinner, and F the stator. The spinner runs freely in its own bearings, C, and is not mechanically connected with the shaft. The primary winding on the inner surface of the spinner is connected with the supply by the slip rings D. The winding constituting the primary of the regulating motor is arranged on the outer surface of the spinner, and is connected with the supply by the slip rings E. G, G are surfaces against which is applied the brake to control the conditions of rest or motion of the spinner.

CHAPTER XIV

THE ALTER-PHASE SYSTEM FOR SHIP PROPULSION

IN British patent No. 30556 of 1909, Mr. Mavor and I describe a system in which not only may use be made of several different frequencies, but in which more than one system of phases may be used, or the latter principle alone, which may be termed the "alter-phase" principle, may be employed. The simultaneous use of *both* principles leads to a high degree of flexibility in the control of the load factor and of the speed. The use of the "alter-phase" principle *alone* has the superiority over the use of the "alter-frequency" principle *alone*, in that more than one system of phases may be readily and efficiently supplied simultaneously *by a single generator*, whereas the simultaneous supply of more than one *frequency* from a single generator, even if it can be termed a commercial proposition, is attended with decidedly unattractive features.

The alter-phase system of control is partly based on the circumstance that the stator winding of an alternating-electricity generator, or of an induction motor, may, by simple control of a few connections, be arranged, for example, to correspond to a three-phase supply for P poles, or to a quarter-phase supply for 0·75 P poles. By the application of this principle to a squirrel-cage induction motor, two different speeds may be obtained by operating the motor from circuits of a given periodicity, according as the supply is three-phase or quarter-phase, and according to the connection of the windings. If, for example, the motor, when connected three-phase, has 8 poles, then, when connected quarter-phase, it will have $(0{\cdot}75 \times 8 =)$ 6 poles. If the periodicity of the supply is 50 cycles per second, then, when the supply is three-phase, the motor's speed will be 375 r.p.m.; and when the supply is quarter-phase, the motor's speed will be 500 r.p.m.

In Fig. 30 are shown, side by side, a winding connected firstly (left-hand diagram) for quarter-phase and 6 poles, and secondly (right-hand diagram) for three-phase and 8 poles. In the left-hand diagram the windings of the two phases are SA–TA and SB–TB. In the right-hand diagram the windings of the three-phases are SA–TA, SB–TB, and SC–TC. In Fig. 31 the winding is repeated, but instead of inter-connecting the coils at the armature, they are led away to a controller, which, in the one position, combines the coils into a three-phase 8-pole winding, and, in the other position, throws the

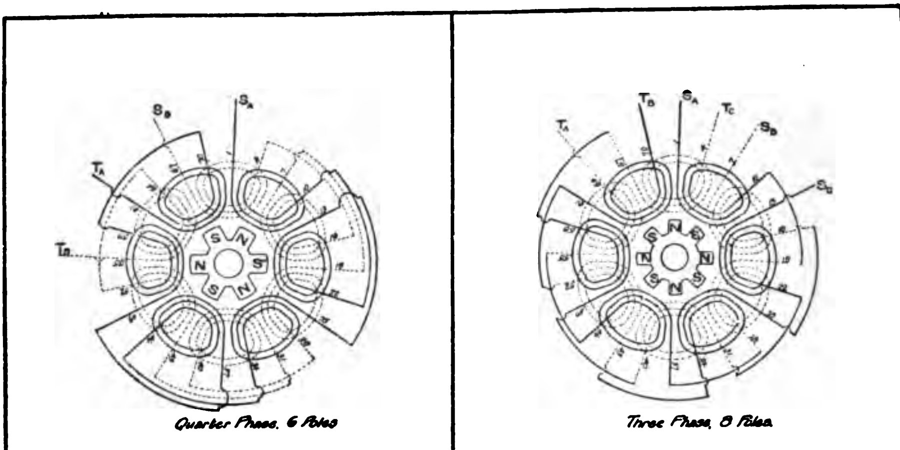


FIG. 30 A 72-SLOT WINDING WITH 6-POLE QUARTER-PHASE AND 8-POLE THREE-PHASE CONNECTIONS

coils into a quarter-phase 6-pole winding. The number of controller points shown in Fig. 31 may be considerably reduced, but, for explanatory purposes, the connections shown are sufficiently appropriate.

Instead of the above type of winding, which may be termed a "spiral" winding, there is the alternative of employing so-called "lap" windings. In Fig. 32 is shown a lap winding, so designed that the winding pitch is one-seventh of the circumference. This winding is quite suitable for either 8 or 6 poles. By connecting the taps to a controller, as shown, the winding may be made into a three-phase or a quarter-phase winding. Thus, in the right-hand

position of the controller, the winding has 8 poles and is three-phase, while in the left-hand position it is quarter-phase and has 6 poles. It is not exclusively quarter-phase and three-phase which can be employed. So-called six-phase connections, which are really only a special case of three-phase connections, may lead to preferable results. A much wider departure introduces five phases, or seven,

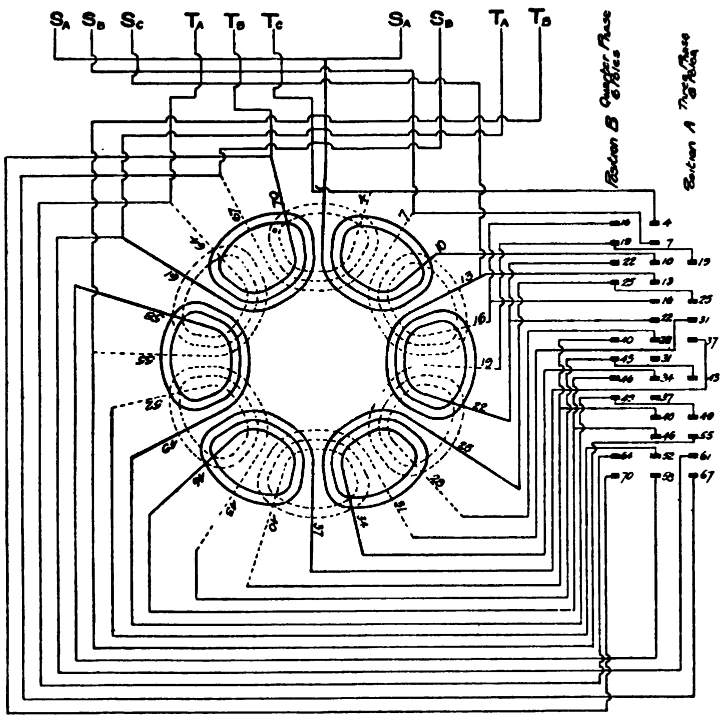


Fig. 31.—The 72-Slot Winding of Fig. 30 connected up to a Controller for effecting the Pole and Phase-changing Arrangements.

or more. Furthermore, it is often preferable, instead of employing two distinct supplies (the one three-phase and the other quarter-phase), to obtain both from a single supply by suitable methods. Thus, in Fig. 33 is indicated diagrammatically a 6-pole generator with a lap-wound stator. The full-line taps provide a three-phase supply, and the dotted-line taps provide a quarter-phase supply. Again, to obtain the advantages of so-called six-phase windings, it

may be preferable, instead of modifying the winding connections, to interpose transformers, and employ the more usual types of dis-

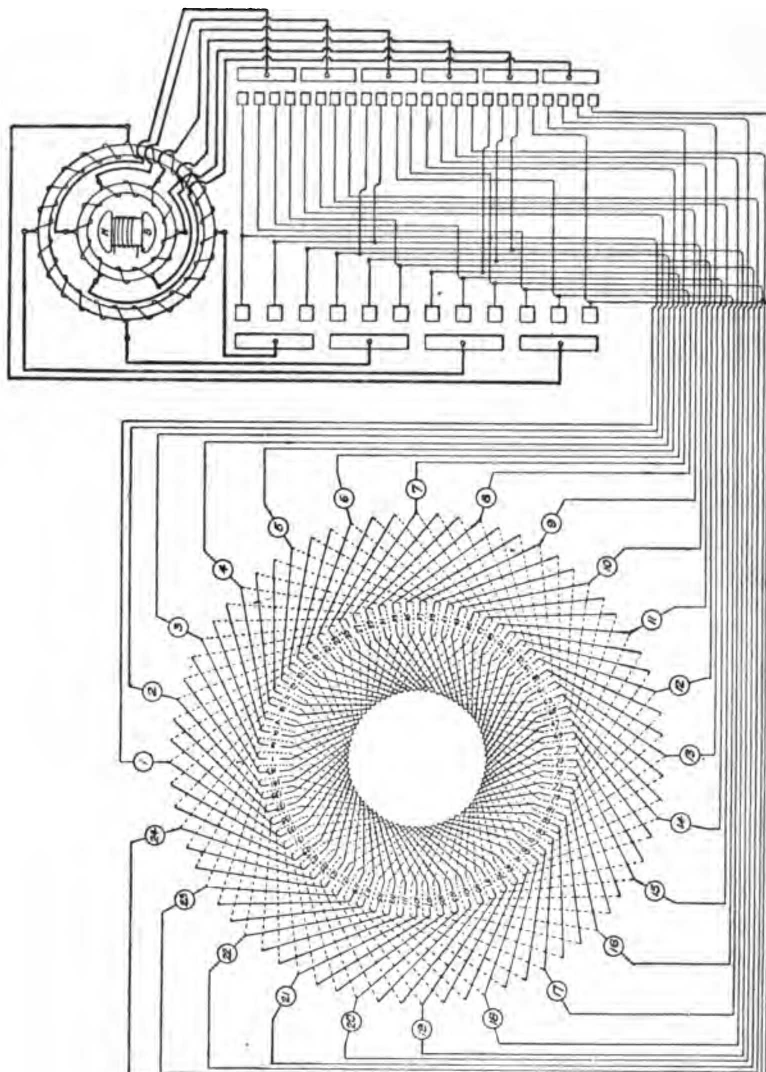


FIG. 32.—Lap Winding with Controller for changing the Connections to constitute either a 6-Pole Quarter-Phase, or an 8-Pole Three-Phase Winding.

tributed three-phase lap-windings. These various suggestions, however, relate to details which, while they should be kept in mind in

dealing with concrete cases as they arise, need not be entered upon more fully in these general explanatory remarks.

For purposes of explanation, I propose to consider a simple case of the application of the general principles of this alter-phase, multi-frequency system to ship propulsion. Let the ship's engine-room contain a 50-cycle generator and a 25-cycle generator. Let each armature of each generator be provided with two windings, the one for supplying three-phase electricity and the other for supplying

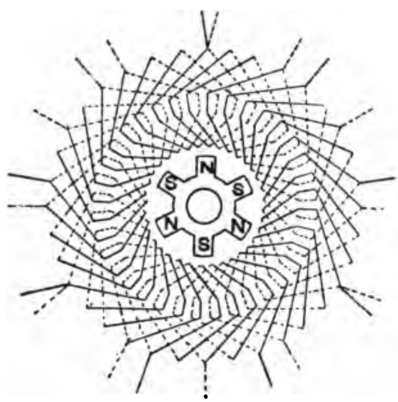


FIG. 33.—Six-Pole "Lap" Winding, showing Full-Line Taps to provide Three-Phase, and Dotted-Line Taps to provide Quarter-Phase Supply.

quarter-phase electricity. There is no complication whatsoever in such an arrangement. Thus we have from the two generators four different supplies:—

Generator I.	Three-phase at 50 cycles Quarter-phase at 50 cycles
Generator II.	Three-phase at 25 cycles Quarter-phase at 25 cycles

Instead of the above arrangement, it may be preferred to have only one winding (say a three-phase winding) on the armature of each generator, and to obtain two-phase electricity by interposing some suitable phase-transforming device. There are various devices of this sort. One of them, which requires only static transformers,

is based on the so-called "Scott" connection of two transformers. These alternatives, again, relate merely to detail, and space limitations will not permit of their further consideration.

Four-speed Equipment

In applying this method to obtain four speeds, there may be employed on the propeller shaft two motors, A and B. The investigation may be carried out in the following tabular form:—

Designation of motor.	Phase variety.	Number of poles.	Cycles per sec.	r.p.m.	Order of Speeds.
A	Three-phase	16	50	375	III
			25	188	I
	Quarter-phase	12	50	500	IV
			25	250	II
B	Three-phase	8	50	750	V
			25	375	III
	Quarter-phase	6	50	1,000	VI
			25	500	IV

Rejecting the cases of 750 and 1000 r.p.m., there remain four useful speeds, for which the data, arranged in the order of the increasing speeds, are brought together in the following table:—

Designation of speed.	Speed in r.p.m.	Ratio of speed at each point to lowest speed.	Percentage increase in speed over next lower speed.	Designation of motor or motors available.	Phase variety.	Number of	
						Poles.	Cycles.
I	188	1·00	—	A	Three	16	25
II	250	1·33	33	A	Quarter	12	25
III	375	2·00	50	A	Three	16	50
				B	Quarter	8	25
IV	500	2·67	33	A	Quarter	12	50
				B	Quarter	8	25

For the two lower speeds motor A would alone be employed, as also only the 25-cycle generator. For the two higher speeds the propeller may be driven by both motors, and the electricity is provided by both generators. The maximum power required by A alone

is that corresponding to a propeller speed of 250 r.p.m., whereas A plus B must provide power for 500 r.p.m. This doubled speed would require approximately eight times as much power. Consequently, if the full capacity required in a particular case is, say, 8000 h.p., the A motor could well be a 1000-h.p. motor, and B a 7000-h.p. motor. But it would often be preferable to carry the subdivision further, and replace B by two motors, each of 3500 h.p. capacity. We may designate these motors A, B–I and B–II. For the 25-cycle generating set an 800-kw. generator would be provided, and for the 50-cycle set a 6000-kw. generator. When the vessel is required to run a considerable distance at a propeller speed of not over 250 r.p.m., the 50-cycle generating set would be shut down. For the two higher speeds the motor A would be of but little account, since it constitutes only some 15 per cent. of the total capacity. Consequently, motor A should certainly be cut out for the third speed, and probably also for the fourth, *i.e.* the highest speed.

Thus the schedule works out as follows:—

Designation of speed.	Speed in r.p.m.	Approximate aggregate h.p. required at propeller shaft.	Motor or motors in service.	Generating sets in service.
I	188	440	A	800 kw.
II	250	1,000	A	800 kw.
III	375	3,500	B–I	6,000 kw.
IV	500	8,000	B–I and B–II	6,000 kw.

These results have not been worked up with the care appropriate to the application of the principle to an actual case, but more for the purpose of indicating the method of procedure and the points requiring to be investigated. There is no reason to believe that they will, in all respects, agree with the results which would be obtained after more exhaustive investigation. In such a preliminary examination as this, it is reasonable to expect that many considerations of great importance, which might greatly affect the question of the preferable combinations, would be overlooked. Nevertheless, my purpose of using a concrete case to more clearly explain the underlying principles has been sufficiently well served by the plan here followed.

Alternative Four-Speed Equipment

Let us now take another case in which two motor types are again employed. We may again take 25 and 50 cycles as the two periodicities. The assumptions are given in the following table:—

Motors.	Phase.	Poles.	Periodicity.	R.p.m.	Order of speeds.
A	Three	16	50	375	III
			25	188	I
	Quarter	12	50	500	IV
			25	250	II
B	Three	12	50	500	IV
			25	250	II
	Quarter	8	50	750	—
			25	375	III

In this case, the three-phase speed of motor B is equal to the quarter-phase speed of motor A, instead of two-thirds of the quarter-phase speed of motor A, as in the previous proposition. The above data lead to the next table:—

Designation of speed.	Speed in r.p.m.	Ratio of speed at each point to lowest speed.	Percentage increase in speed over next lower speed.	Designation of motor or motors available.	Phase variety.	Number of	
						Poles.	Cycles.
I	188	1·00	—	A	Three	16	25
II	250	1·33	33	A	Quarter	12	25
				B	Three	12	25
III	375	2·00	50	A	Three	16	50
				B	Quarter	8	25
IV	500	2·67	23	A	Three	12	50
				B	Quarter	12	50

For this case the top speed is carried by the 50-cycle generator alone. Consequently, this generator should be of some 7000-kw. rated capacity. For speeds I and II, the 25-cycle generator is alone employed, and this should be of some 800-kw. capacity. For this scheme, four motors could well be employed on the propeller shaft. These four motors may be designated A, B–I, B–II, and B–III. A and B–I should be of 500-h.p. capacity each, and B–II and B–III should be of 4000-h.p. each. The machinery which should prefer-

ably be run for obtaining the various speeds, is set forth in the following table :—

Designation of speed.	Speed in r.p.m.	Approximate aggregate h.p. required by propeller.	Motor or motors in circuit.	Generating sets.
I	188	440	A	800 kw.
II	250	1,000	A and B–I	800 kw.
III	375	3,500	B–II	7,000 kw.
IV	500	8,000	B–II and B–III	7,000 kw.

It would require a detailed investigation, covering cost, weight, coal consumption, and many other practical considerations, to decide between this and the preceding example. Furthermore, it is evident that there are many other alternatives which should be kept in mind. Thus the periodicities need not be 50 cycles and 25 cycles, but might have various other values. Thirty and 20 cyles, or 50 and $33\frac{1}{3}$ cycles, lead to useful combinations.

Eight-Speed Equipment

It will be interesting to call attention to another scheme of this sort which I have worked out roughly. Its striking characteristic is the large number of speeds obtained. In this scheme the starting-point is to employ three types of motors, each type having a different number of poles for three-phase, as also, of course, for quarter-phase. The first steps in the working out of the scheme are carried out in the following table :—

Motor.	Phase variety.	Number of poles.	Periodicity.	R.p.m.	Order of speeds.
A	Three	64	50	93·8	VI
			25	46·9	I
	Quarter	48	50	125·0	VIII
			25	62·5	III
B	Three	56	50	107·0	VII
			25	53·5	II
	Quarter	42	50	142·5	IX
			25	71·3	IV
C	Three	48	50	125·0	VIII
			25	71·3	III
	Quarter	36	50	167·0	X
			25	83·5	V

From these data the following table may be deduced :—

Designation of speed.	Speed in r.p.m.	Ratio of speed at each point to rated speed.	Percentage increase in speed over next lower speed.	Designation of motor or motors available.	Phase variety.	Number of	
						Poles.	Cycles.
I	46·9	1·00	—	A	Three	64	25
II	53·6	1·14	14	B	Three	56	25
III	62·5	1·33	17	C	Three	48	25
IV	71·3	1·52	14	B	Quarter	42	25
V	83·5	1·78	17	C	Quarter	36	25
VI	93·8	2·00	12	A	Three	64	50
VII	107·0	2·28	14	B	Three	56	50
VIII	125·0	2·67	17	A C	Quarter Three	48 48	50 50
IX	142·5	3·04	14	B	Quarter	42	50
X	167·0	3·57	17	C	Quarter	33	50

Let us consider a case where it is only proposed to make use of the first eight out of the ten speeds shown in the table. This gives a range of 1·00 to 2·67, and has the advantage that A- and C-type motors are both available at the top speed of 125 r.p.m. Let us assume, for illustrative purposes, that 8000 h.p. is required at this speed. Then we may supply a 6000-kw. 50-cycle generator, and a 3000-kw. 25-cycle generator. An inspection of the table shows us that the aggregate capacity of the B-type motors must suffice for a speed of 107 r.p.m., *i.e.* for 5000 h.p. Let us provide three 1800-h.p. motors of this type, and designate them B–I, B–II, and B–III. Motors of type A must alone suffice for a speed of 93·8 r.p.m., *i.e.* for 3500 h.p. Let us supply two 1800-h.p. A-type motors, and one 2400-h.p. C-type motor. Thus the aggregate installation of motors is as follows :—

	Rated h.p. of each motor.	Number of motors.	Aggregate capacity.
Type A	1,800	2	3,600 h.p.
" B	1,800	3	5,400 "
" C	2,400	1	2,400 "
	Totals	6	11,400 "

There is nothing special about any of these six motors; and

consequently each will be a thoroughly light motor for its rating. The aggregate weight of the six motors will thus be thoroughly reasonable when the many efficient speed steps are taken into consideration. It is true that 11,400 h.p. is installed, whereas, at maximum speeds, only 8000 h.p. is in circuit, but 11,400 h.p. of standard single-speed motors, without any special features, will be lighter than the 8000 h.p. of motors with special features essential with other systems, even when less speed-flexibility is obtained.

It will be seen that speeds I to V are obtained from a single frequency, namely, 25 cycles per second, and that speeds VI to X are also obtained with a single frequency of supply. Thus, by the use of the principle of employing more than one system of phases, and not employing (even in conjunction with it) the multi-frequency principle, a very flexible system is obtained. The combination of *both* principles, however, gives very great flexibility of speed-control, together with high efficiency; for it will be noted that the subdivision of the motors may be so carried out that whatever motors are in circuit are worked at fairly considerable percentages of their rated loads, and consequently well up on their efficiency and power-factor curves. In other words, the load-factor of each component machine is high.

For the case of a given vessel, route, speed, length of run, etc., the appropriateness or non-appropriateness of this system should be first roughly tested by preliminary surveys such as those above described.

I consider that in the interests of obtaining a high load factor, it is usually undesirable to combine two or more of the component motors into a single, larger motor. But, on the other hand, such combinations reduce the inital capital outlay, and this will sometimes render their use appropriate. Thus, in the last example, instead of motors A, B, and C, with 64 and 48, 56 and 42, and 48 and 36 poles, a single motor could be built with a stator provided with three windings.

Further careful study reveals various arrangements for reducing the number of windings, and of selecting amongst the six winding arrangements desired for the compound machine, other arrangements or combinations rendered practicable by bringing all the windings upon one stator, instead of having them on three separate stators.

Thus the recurrence of 48 poles in types A and C suggests practicable modifications. The subject opened up is so extensive that it must suffice to simply state that there are many more-or-less obvious

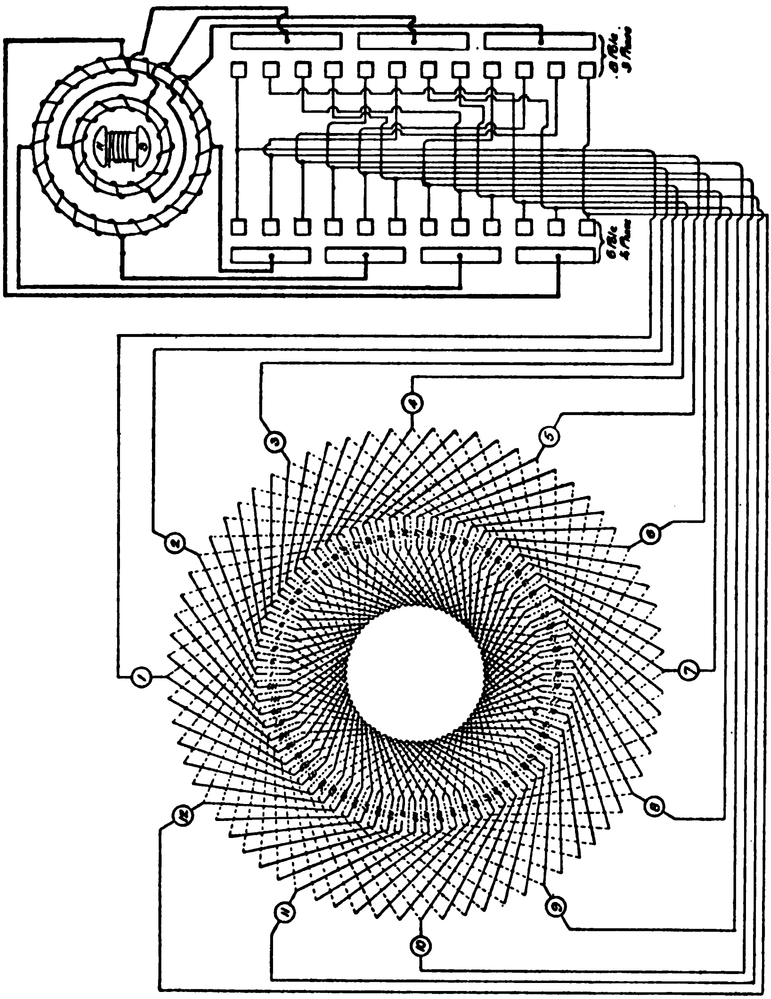


FIG. 34.—Lap Winding with Controller for changing the Connections to constitute either a 6-Pole Quarter-Phase or an 8-Pole Six-Phase Winding.

alternatives. Every new combination of poles, phases, and cycles which one subjects to investigation leads to the disclosure of new methods of treatment. There have above merely been indicated three of the simplest and most fundamental combinations, and it is

thought that these examples amply illustrate the fundamental principles of the system.

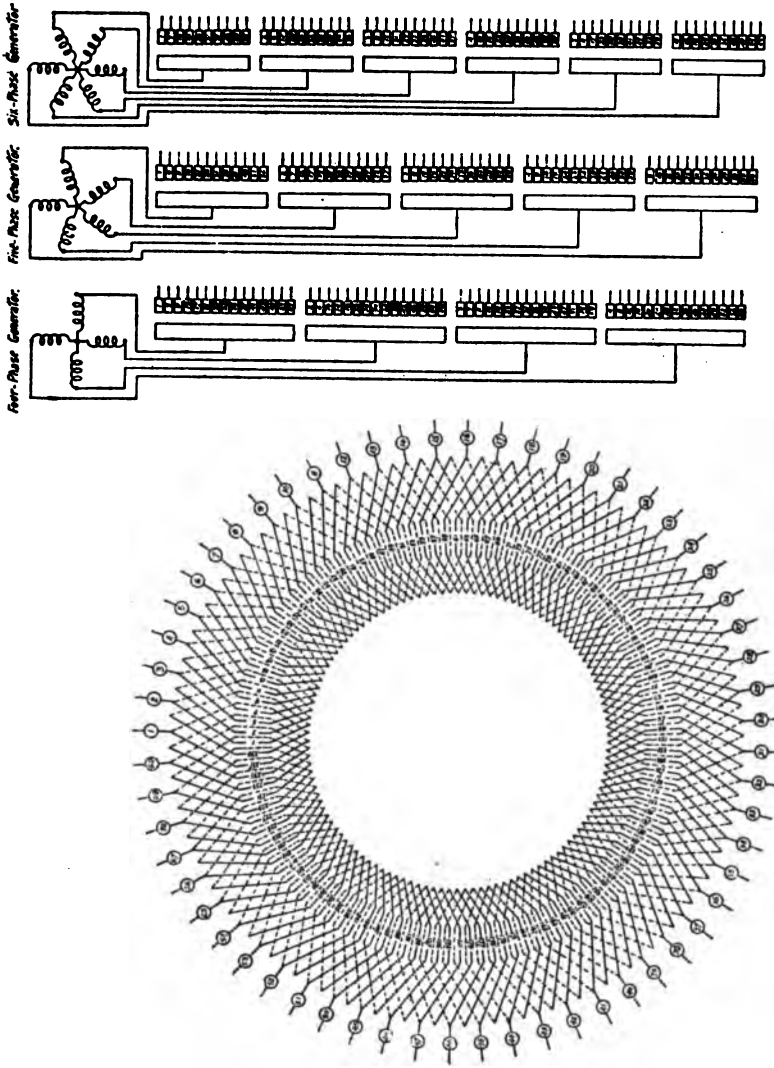


FIG. 35.—Lap Winding with 240 Conductors, showing Tappings to Controller to operate Four, Five, and Six Phases.

A six-phase and quarter-phase system of working is indicated in Fig. 34. The six-phase connection, with its six taps per pair of poles, is more effective than a corresponding three-phase connection, such

as that indicated in Fig. 32. Still other systems of phases may be employed. Thus in Fig. 35 is shown a stator winding of the lap type, and with 240 conductors. It is so connected that, according as four, five, or six phases are appropriately led to sixty equidistant taps taken from the winding, the motor will have 30, 24, or 20 poles. If operated from a 25-cycle circuit, the three corresponding speeds are 100, 125, and 150 r.p.m. At the right-hand side of Fig. 35 are indicated diagrammatically three generating systems, supplying respectively four-, five-, and six-phase electricity. The three vertical rows of numbered terminals indicate the controller contacts which are to be engaged when connecting the motor winding to its four-phase, five-phase, or six-phase generator. I consider that insufficient attention has heretofore been given to the important possibilities of these larger numbers of phases. Instead of a lap winding as in Fig. 35, we may employ a spiral winding. Fig. 36 shows such a plan worked out for a 20-, 24-, and 30-pole motor.

The alter-phase principle may be employed in connection with the cascade control of motors to which allusion has already been made at p. 107 of Chapter XII. The combination of cascade control with the alter-phase principle is described in the patent to which reference has already been made, *i.e.* Mavor and Hobart's B.P. No. 30556 of 1909. In the more customary cascade systems, there are only two motors, and in such instances the alter-phase principle just referred to may be applied to either the primary or the secondary motor, or to both motors. Taking a case where it is applied to both motors, and where three-phase and quarter-phase sources of supply are available, the primary motor may be operated either from the three-phase source or from the quarter-phase source. If, in the first case, the motor has 8 poles, it will, in the second case, have 6 poles. As a particular instance of one amongst many alternative ways of applying the principle, assuming that the electricity be supplied to the stator of the primary motor, that this stator has a winding of the "spiral" type, that the rotor has a winding of the "lap" type, and that the "winding pitch" of the rotor is about one-seventh of the circumference, then the rotor winding will be quite suitable for either 8 poles or 6 poles. A number of taps may be led off from this winding suitable for providing 8-pole three-phase, 8-pole quarter-phase, 6-pole three-phase, and 6-pole quarter-phase. For

the three-phase arrangements there will be provided three equidistant taps per pair of poles, and for the quarter-phase arrangements there will be provided four equidistant taps per pair of poles. These taps may be suitably grouped and led to slip rings. The secondary motor may have its stator provided with a winding suitable for 8 poles

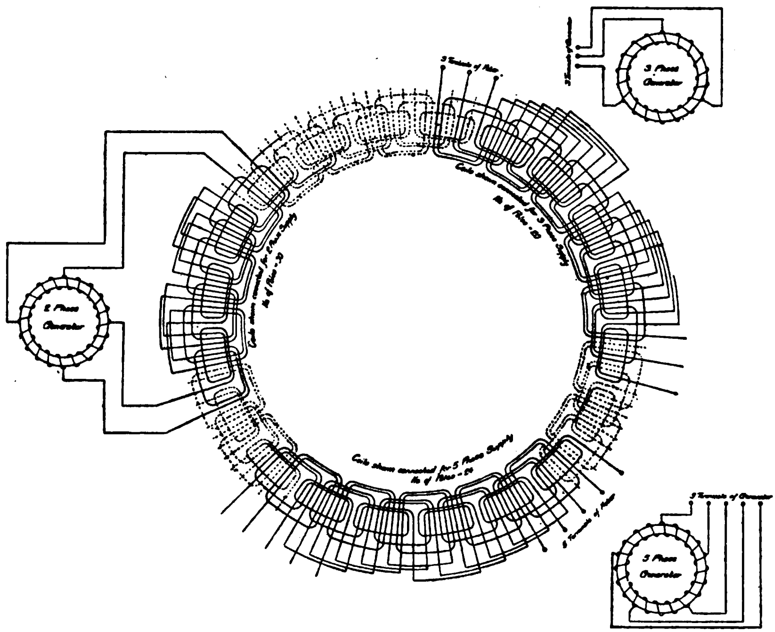


FIG. 36.—Winding with 240 Conductors suitable for running on Two, Three, or Five Phases.

when arranged three-phase, and for 6 poles when arranged quarter-phase. The rotor of the secondary motor may be of the squirrel-cage type, or it may have distinct windings leading to collector rings. The arrangement is indicated diagrammatically in Fig. 36A, in which M is the stator of the primary motor, N the rotor, current from which is conducted by the slip rings O to the stator P of the secondary motor. Q is the wound or squirrel-cage rotor of the secondary motor, and R a sliding collar, guided by a key R_1 and carrying insulated contacts which are arranged to co-act with insulated contacts on the plate S to effect a 6-pole connection of the winding of the rotor N, or with insulated contacts on the plate T to change the connection to 8-pole

relationship. With this arrangement, or by some equivalent arrangement, or by the use of a larger number of slip rings in place of the three rings indicated at O, if the system is supplied at a periodicity of 25 cycles, we may obtain the following useful speeds:—500, 375, 250, 214, and 187 r.p.m. With alteration in the frequency of supply, there will be a corresponding alteration in the speeds.

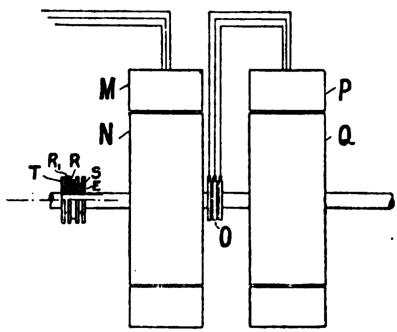


FIG. 36A.—Alter-Phase Cascade Control.

Obviously, a large number of alternative arrangements based on these same ideas are available. Stators and rotors may be alternatively arranged in the ways indicated. The rotor of the primary motor may supply exclusively three-phase current, which may be transformed into quarter-phase by a stationary transformer, or *vice versâ*. Other systems of phases, such for instance as five, six, and seven phases, may be employed. The invention may be employed in conjunction with various already known methods. The stators or rotors of one or both motors may be provided with more than one winding, and these windings may be fundamentally suitable for the same numbers of poles or for different numbers of poles, or for the same system of phases or for different systems of phases.

At p. 154 is given a description of a multi-frequency generator devised with reference to the requirements of the alter-phase, alter-frequency system.

CHAPTER XV

THE DURTNALL SYSTEM OF PROPELLING SHIPS[1]

MR. WILLIAM P. DURTNALL has for several years devoted a large amount of attention to the electric propulsion of ships, and is exploiting a system under the name of the "Paragon System." In British patent No. 17248 of 1905, entitled, "Improvements in and connected with the propulsion of railway, tramway, road, or similar vehicles, boats, and the like," granted to Hart and Durtnall, a closing paragraph reads as follows, the four italicized words being in accordance with the specification as amended under date of March 16, 1909:—

"It is possible to control from one or more positions, such as the captain's bridge; and also by winding the motors with two or more magnetic poles *more than the generator*, means are thus provided so that the electric generator can be run at very high speed, and the motors connected with the propellers run slower with increased torque, which is a great advantage when high-speed prime movers, such as steam turbines, are employed."

The claims of this patent are as follows:—

1. In a method of propelling a vehicle or boat, comprising the combination of a prime mover, an electric generator, a motor in electrical connection therewith, and appropriate transmission gear, the use of an electric generator having a revolving magnet or magnets and a stationary armature, the windings being arranged for polyphase alternating current.

2. In a method of propelling a vehicle or boat, as claimed in Claim 1, adapting the exciter so that the excitation of the electric

[1] In preparing this chapter, I have made liberal use of notes with which Mr. Durtnall has kindly supplied me. My thanks are also due to Mr. Durtnall for providing me with the illustrations numbered Figs. 37 to 40.

generator field-magnet or magnets may be varied, substantially as and for the purpose hereinbefore described.

Durtnall regards this as a "master patent for three-phase alternating-current driving of ships, with high-speed prime mover, and generator with fixed armature, and arranging the motor driving the propeller with *more poles than the generator*, so that the motor shall run at a lower speed than the generator." Durtnall states that in this patent "the first suggestion is made to get economy in full by means of polyphase alternating-current power generation and transmission, the necessary speed regulation being obtained by means of the variable frequency which may be obtained by varying the speed of the prime movers." He considers that "the patentable matter consists of the means of obtaining a speed reduction, so that steam turbines or other prime movers can run at high-revolution speed, and so get great efficiency of fuel in producing the power, and that the maximum of thrust may be obtained for the propulsion of the ship by using slow-revolution, large-blade-area screw propellers." Durtnall mentions that, "as a system of driving ships, it has been maintained by the British Patent Office Controller in two recent cases of successful opposition." One of these was "against the granting to Parsons of Patent No. 6177 of 1909, in which Parsons proposed to use a polyphase alternating system with the windings in certain sections." As the result of the opposition the claims were limited to the *windings only* in connection with such ship-propulsion systems, and the patent "disclaimed the use of motors having more poles than the generators." The other patent opposed by Durtnall was the British Thomson-Houston Co.'s No. 19872 of 1909, relating to the propulsion of ships by a combination of polyphase generating plant, with high-speed prime movers and slow-speed induction motors for driving the propellers. In this patent it was proposed to use, in conjunction with the electrical plant, a low-pressure slow-speed turbine, coupled to the propeller shaft, together with the motor; the exhaust steam from the high-pressure high-speed turbine driving the electric generators, was further utilized in the above low-pressure turbine on the propeller shaft. In view of the opposition, the patent was revised and disclaimed polyphase alternating current as a means of transmission, and for arranging the necessary speed reduction from the high-speed

turbines to the slow-speed propeller shafts. Durtnall points to his 1905 patent as evidence that it was already at that date apparent to him that a system employing high-speed generators, *fixed armatures*, and revolving fields constituted an eminently appropriate way of carrying out a large-powered job in a large ship. There are described in his patent means for varying the propeller speed by changing the speed of the prime mover. But this, when done in conjunction with the ordinary method of direct-coupled turbine-driving, involved waste of fuel when the propellers had to be run at a low-speed, as when coming into harbour or in the case of fogs, and furthermore it involved running all the prime movers even at these low speeds. A further disadvantage arose from the circumstance that squirrel-cage motors do not start up satisfactorily unless a low frequency is employed. This required that the revolving magnets should always remain excited, and that the motors should be run up to speed at the same time as the exciters. There was also the disadvantage that in order to reverse it was necessary to slow down the turbines before reversing two out of the three connections to the motors. Durtnall considers that, while his original system was thoroughly within the range of practice, a much better arrangement is proposed in his subsequent British patent, No. 23396 of 1908.

The so-called "Paragon" system is based upon this patent, in which Durtnall again draws attention to the saving in fuel which may be effected by running the turbines or other prime movers at a much higher revolution speed than that of the screw propeller. In this (1908) patent, Durtnall proposes to generate the current with variable frequency. This provides means for operating the induction motors at any of several speeds, and Durtnall states that it permits of obtaining "the high reversing-torque which is essential on reversing a screw propeller when the vessel is proceeding ahead, and requires either to be stopped or made to go astern." The system provides, Durtnall explains, at all speeds, substantially the same high fuel economy as that obtained when the vessel is proceeding at full power and speed. When the vessel is proceeding at a slow speed, as is required on certain occasions, even with cargo vessels, and nearly always with war vessels, a certain number of the prime movers are shut down.

In Fig. 37 is shown an instance of a proposed application of the

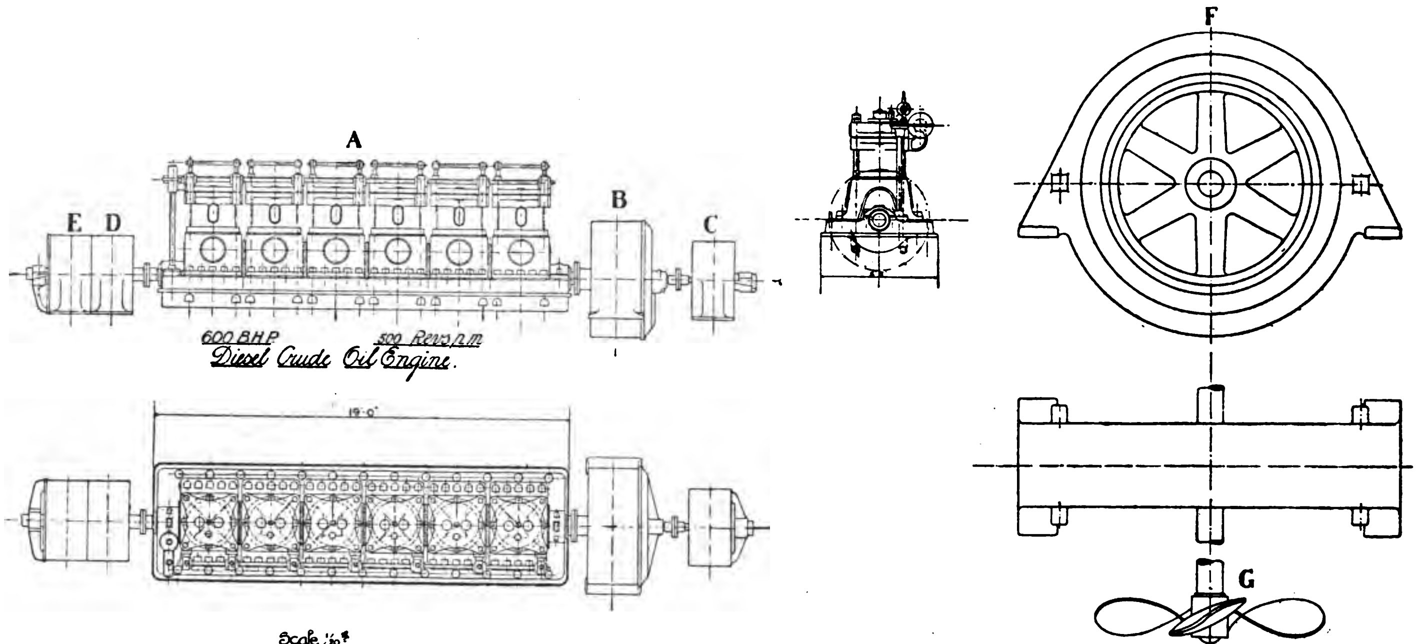


FIG. 37.—Durtnall's "Paragon" System of Electrical Power Generation, Transmission, and Speed Regulation, for Ship Propulsion with Diesel Internal-Combustion Engine.

Durtnall system in connection with Diesel engines, or some other form of internal-combustion engines. In this instance the system is arranged for the prime movers to run at a constant speed of 500 r.p.m., and provides that the propellers may be run at any one of five different speeds. No slip-rings or resistances are employed at the motors. A is the Diesel high-speed engine running at a constant speed of 500 r.p.m. It is direct-connected to the three-phase alternating-current generator B. At the same end of the engine shaft is also mounted the primary member of a "transformer generator," C. At the other end of the engine shaft are mounted the primary members of two other transformer generators, D and E. The motor is shown at F, and the propeller at G. The motor shown in this instance is wound for 56 poles, and has a squirrel-cage rotor. It may be run at any one of five speeds by means of the variable frequency supply provided by the generator B, and the three transformer generators, C, D, and E. The generator B is wound for 8 poles, whilst the transformer generators C, D, and E have both their rotors wound for 4 poles. In each case the primary windings are on the rotors. The generator and the three transformer generators are all mounted on the same shaft, and are consequently all driven at the Diesel engine's constant speed of 500 r.p.m. The various speeds are obtained on the motor by coupling it to the terminals of the different machines by means of suitable control gear. All changes of connections are effected under no-voltage conditions by taking the excitation off the generator B, the whole system then becoming dead and remaining so until, after the change of connections has been effected, the excitation is again applied to the generator.

Description of the Speed-Control

First Speed.—The exciter is put on to the slip-rings of the revolving field-magnet of the generator B, and a three-phase current at a periodicity of 33·3 cycles per second is delivered to the slip-rings on the primary member of the transformer generator C. The direction of the current in the windings of the primary of C is such that the resulting magnetic flux revolves in the counter direction to that in which the rotor is being driven by the engine. Since the rotor is wound for only 4 poles as against the 8 poles of the generator,

and since they are both on the same shaft, the magnetic flux revolves backwards twice to every forward revolution of the rotor core. Consequently the secondary winding on the stator delivers a three-phase current at half the periodicity, namely, at a periodicity of 16·7 cycles per second. When supplied at this periodicity, a 56-pole motor runs at approximately 34 r.p.m. (as may be seen by consulting the table on p. 111). The 56-pole motor is direct-connected to the propeller shaft, and consequently the first speed of the screw is 34 r.p.m.

SECOND SPEED.—When it is desired to increase the vessel's speed above 34 r.p.m., the excitation is switched off from the generator, and whilst under the no-voltage condition the controller effects connections by which the motor is supplied directly from the generator B. When this change in the connections has been effected, the generator is again excited, and current goes to the motor at a periodicity of 33·3 cycles per second, causing the motor to accelerate to a speed of 68 r.p.m.

THIRD SPEED.—The third speed is obtained by so changing the connections (again under no-voltage conditions) that the current from the generator is again sent into the primary windings of the transformer generator C, but in the opposite direction to that employed for the first (lowest) speed, by reversing two out of the three supply leads between B and C. As a result, the magnetic flux set up in the rotor of C now revolves in the same direction in the rotor core as that in which the rotor core is being driven by the engine, so that the 4-pole secondary winding of C is, per revolution, subjected to twice as great a periodicity of reversal of the magnetic flux as would be the case were the flux set up by a stationary primary. We may express the state of affairs by stating that there is a mechanically-imparted frequency superposed upon an electro-magnetically imparted frequency. The aggregate result is that the 4-pole secondary winding supplies to the 56-pole motor a periodicity of 50 cycles per second, this being made up of a periodicity of 16·7 cycles per second which is mechanically imparted direct from the engine, added to a periodicity of 33·3 cycles per second which is electro-magnetically imparted from the 8-pole generator B. The 56-pole motor now drives the screw at a speed of about 103 r.p.m.

FOURTH SPEED.—The three lowest speeds are of value when vessels, such as cargo vessels, are proceeding in foggy weather, or

when coming in or out of harbour, or when navigating certain inland waterways. At such relatively low speeds the power required from the motor is low, and the load factor of the plant is poor. But, nevertheless, the economy of the engine is higher when running at its normal speed of 500 r.p.m. than would be the case without the electrical apparatus, since it would then be necessary to obtain the low speeds of the vessel by corresponding reductions in the revolution speed of the engine. Such reductions in the revolution speed of internal-combustion engines are inconsistent with maintenance of the economy corresponding to their normal speed.

In order to go up to the fourth speed, the connections on machines B and C remain the same as for the third speed, but before going to the motor, the current from the secondary windings of C is sent into the primary member of D. Since D also has 4-pole windings, and since it is also driven by the engine at a speed of 500 r.p.m., the windings of the secondary member deliver a 66·7-cycle current, three parts of this periodicity being imparted to it electromagnetically from B and C, and one part being imparted to it mechanically in virtue of the speed at which its rotor is driven by the engine, the magnetic flux revolving in the rotor core in the same direction in which this is mechanically driven. When this 66·7-cycle current is carried to the 56-pole motor the latter runs at a speed of about 139 r.p.m. The power is also more (since it increases, roughly, as the cube of the speed), but the total power is now supplied by the machines B, C, and D. The engine will still be running at its constant speed of 500 r.p.m. and will be carrying, say, 75 per cent. of its full load.

Fifth Speed.—For the fifth (*i.e.* the highest) speed, the connections are so modified that the current from D is sent into the primary (*i.e.* the rotor) windings of E, and a current of 83·3 cycles per second is sent to the 56-pole motor from the secondary (*i.e.* the stator) windings of E. At this top voltage and current the motor accelerates to about 174 r.p.m., and the boat proceeds at top speed and power. Under these conditions the engine is distributing its power between machines B, C, D, and E, each of which, in turn, adds its given frequency and extra voltage.

Reversing.—Durtnall points out that it must not be overlooked that, although full power is not required for astern running,

nevertheless a very large torque has to be overcome when attempting to reverse a screw propeller when the boat is proceeding in the ahead direction at full speed. In any system of ship propulsion provision must be made for such conditions in the interests of safety, and to meet the conditions required by shipowners, insurance companies, and other interests. Durtnall employs squirrel-cage induction motors, "because of their simplicity and high efficiency, and because of their comparatively low weight per b.h.p. at given revolution speed." But although "such motors are very efficient when they are running at full speed, and will develop a heavy running torque, if the current were to be suddenly cut off for any reason, and the motor brought to a standstill, then, if the current were again turned on at the frequency corresponding to full speed, such motors would not develop sufficient starting torque to even *start themselves light*, without taking into consideration the heavy torque to be overcome when reversing the propeller." Durtnall overcomes this difficulty by means of his multi-frequency supply. On requiring to reverse the propeller, "all that is necessary is to throw the connections into the *first-speed* arrangement, but with two out of the three phases *reversed*." Thus, if the vessel is going full speed ahead, the power is taken off by ceasing to supply excitation to the generator. The connections are then rearranged as above indicated, and when the excitation is again applied to the generator, the magnetic field in the motor will revolve in the reverse direction with the 16·7-cycle frequency, just as for the *first speed ahead*. The rotor will still travel in the "ahead" direction, the screw being pulled through the water by means of the travelling vessel, the pressure of water being then on the front of the blades of the propeller. Thus the propeller is then actually driving the rotor of the motor still in the ahead direction. But the magnetic flux in the core of the motor's stator is now revolving in a direction to oppose this motion; heavy currents are set up in the squirrel cage of the rotor, and the propeller is thereby braked. The vessel slows down to rest, and the low-frequency currents which are being supplied to the motor suffice to start it up with heavy torque in the reverse direction until the *first speed astern* is reached. Other astern speeds, if required, are obtained similarly to the corresponding ahead speeds. But with a view to obtaining high efficiency in the ahead direction, screw propellers have their blades so curved that the

efficiency in the astern direction is lower, and consequently the speed of the vessel will be lower for a given revolution speed of the screw.

Durtnall states that the above-described system is "one which can be used for small passenger or cargo boats up to the limit of size of the Diesel engine." He points out that "in this method of power generation and transmission, *several* prime movers can be used to drive the different generators and transformer generators." Thus, in the case employed in the example already described, instead of one 600 b.h.p. engine driving *all* the machines, four 150-b.h.p. engines might have been used, one to drive each of the machines B, C, D, and E. By this plan, when the boat is proceeding at the second speed for any length of time, only one engine (*i.e.* that driving B) will be required to generate the current necessary for the propulsion of the ship at the relatively low speed corresponding to the motor speed under these conditions. This introduces the advantage that both the engine and the generator will be operated in the neighbourhood of full-load conditions, and hence the propelling plant will show excellent economy, notwithstanding the vessel's low speed. This is a very important consideration for such a case as a warship, and also, though in much less degree, for a cargo boat, since the former has constant occasion to travel at speeds and powers far below the normal capacity of the propulsive machinery; and with cargo boats also this is a consideration, though by no means one of such importance as for a warship.

Durtnall states that "the power transmission efficiency of such a lay-out of plant will be approximately 85 per cent., so that at full load and speed it is possible to get 425 shaft h.p. at a propeller speed of 174 r.p.m. The fuel consumption of the Diesel engine will then be about 0·45 lb. per b.h.p.-hour, and the fuel consumption per *shaft* h.p.-hour will not exceed 0·53 lb. of crude oil. Thus, assuming a vessel speed of 10 knots, 100 tons of crude oil (at 40*s*. per ton) would propel the vessel at full speed for 1000 hours, or over a distance of 10,000 (nautical) miles, thus easily taking her from London to Melbourne at a fuel cost of only £200. A similar vessel, direct-driven by steam at the same revolution speed of the propeller, would, including the driving of the steam auxiliary machinery, consume *at least* some 2 lbs. of coal per shaft h.p.-hour, and would, owing to the extra weight of boilers, etc., require some 600 shaft h.p. to give her

the same speed with the same dead weight or cargo capacity. Consequently, she would require for this 10,000-mile voyage at least 500 tons of coal, which, at 15*s*. per ton, works out at a fuel cost of £373. This, compared with the possibilities of internal-combustion engines and electric propulsion, is a saving of 46 per cent. in fuel cost. In other words, the fuel cost with steam propulsion for this instance, and on the basis of coal at 15*s*. per ton and oil at 40*s*. per ton, works out 85 per cent. higher than the corresponding fuel cost for the alternative proposition with internal-combustion engines combined with electric propulsion."

In Fig. 38, Durtnall illustrates another lay-out of his system.[1] In this instance, Durtnall shows a combination steam job with

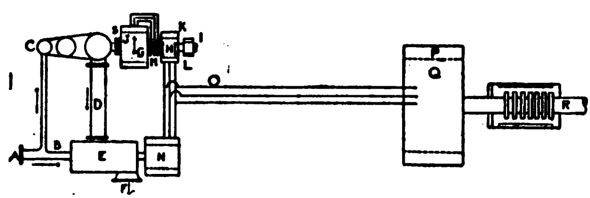


FIG. 38.—Durtnall's "Paragon" System. Proposed Arrangement for an Installation of 830 s.h.p. working a Single Screw, with combination of Reciprocating Steam Engine and Mixed-pressure Turbine.

polyphase alternating-current plant, with high-speed prime movers and a slow-speed induction motor for driving the propeller. The equipment is designed for 830 shaft h.p., which would be appropriate for certain classes of small cargo boats. The plant comprises a combination of a piston steam engine and a mixed-pressure turbine (*i.e.* a turbine taking both exhaust and live steam). These prime movers drive the electric generators G and N, and the transformer-generator H. A is the live-steam delivery-pipe, which is branched to feed both the live-steam end of the turbine B, and the stop-valve end C, of the triple-expansion engine T. The engine T exhausts at, say, one pound above atmosphere, through the exhaust-pipe D, to the low-pressure end of the turbine E. The exhaust steam is again utilized for the production of mechanical power delivered by the

[1] The following description, as well as that of the lay-out described on p. 147, are taken, by permission, from a paper entitled, "The Substitution of the Electric Motor for Marine Propulsion," a paper read by Mr. Durtnall on March 17, 1910, before the Institution of Naval Architects.

turbine, which exhausts into vacuum by means of the exhaust end F. The engine runs at 500 r.p.m., and drives the 4-pole generator G, and the 2-pole transformer-generator H, also the small exciter I; the direction of revolution of all these machines, which have a single shaft, being indicated by the arrow J. On the engine shaft is also mounted the 3-part slip-ring collector M. The three rings are connected to the 2-pole windings of the primary member of the transformer-generator H. The turbine drives the 2-pole rotor of the non-synchronous polyphase, alternating-current generator N, at, say, 1550 r.p.m. The conductors, O, run from the generating plant shown to a squirrel-cage induction motor which drives the propeller shaft. Q is the rotor coupled to the propeller shaft, and P is the stator, which carries a 36-pole primary winding. R is the propeller shaft, which will have speeds of 81, 54, and 27 r.p.m., both ahead and astern.

Explanation of the Operation of the System

Assume that the live steam is turned on the reciprocating engine, which is set running, governed at 500 r.p.m., in the direction marked J; the engine is then arranged to exhaust direct to the condenser, and will thus remain for the first two propeller speeds.

First Speed Ahead.—The exciter I is turned on the slip-rings S, which are coupled to the winding of the 4-pole revolving magnet of the generator. A three-phase alternating current, with a frequency of 16·7 cycles per second, is then produced in the generator armature stationary windings. This current is sent into the slip-rings M, which are coupled to the 2-pole winding on the mechanically-driven primary member of the transformer-generator H, with a result that, the speed being 500 r.p.m., and the generator being 4 poles, and the transformer-generator being only 2 poles, the three-phase current in the primary windings of the transformer produces a revolving magnetic flux which revolves in the opposite direction in the iron of the primary member to that in which it is being driven mechanically, twice for every mechanical turn, so that the 2-pole windings on the stator secondary member of the transformer are excited once for every mechanical turn of the engine. Thus the frequency of the current which may now be coupled

to the motor is 8·3 cycles per second, the motor being wound for 36 poles. It runs at a speed of (allowing 2 per cent. for slip between the revolving magnetic poles in the stator iron and the rotor of the motor) 27·5 r.p.m.

SECOND SPEED AHEAD.—The engine is still running at 500 r.p.m., but the connections are made in such a way, by means of the controller (under no-voltage conditions) that the three-phase current is taken direct from the generator G to the motor, the frequency of the current being 16·7 cycles per second. The motor runs at a speed of (allowing $2\frac{1}{2}$ per cent. for slip) 54 r.p.m.

FULL SPEED AHEAD.—The engine is still run at 500 r.p.m., but the exhaust is then changed so that the engine exhausts into the turbine as explained. Some live steam is sent also to the turbine, so that the turbine runs at approximately 1550 r.p.m. Fig. 38 shows the steam and electrical connections for this speed. The extra power for propulsion at full speed is provided for by the turbine, utilizing the exhaust steam from the high-speed engine for the purpose, as well as a certain amount of live steam to make up the difference, in order that the turbine shall have as high a speed as possible, and also to provide the necessary frequency in order that the motor shall run at (allowing $3\frac{1}{2}$ per cent. slip) 80·5 r.p.m. The electric working is as follows:—

The current is taken from the generator at 16·7 cycles per second, and sent into the primary member of the transformer-generator, in the opposite direction to that in which it was sent when the first speed ahead was on, so that the 2-pole windings of the stator secondary member are excited twice by electro-magnetic rotation, and once by mechanical rotation, with the result that the frequency of the current in the stator member of the transformer is 50 cycles per second.

As the shaft h.p. required at this vessel speed is 830 b.h.p., and as the reciprocating engine is only about 250 b.h.p., the electrical power is raised by the following means. As indicated by the electrical connections, the 50-cycle current is sent into the 2-pole stator winding of the non-synchronous generator that is driven by the turbine, in such a direction that the magnetic poles revolve in the iron of the stationary portion of the generator at a speed of 1500 r.p.m., in the same direction of rotation that the squirrel cage, which is driven by the turbine, is running at 1550 r.p.m., with a result

that further power is delivered to the conductors running to the motor, which then runs at the speed named and delivers 830 b.h.p. to the propeller shaft R. The turbine gives off 730 b.h.p., the engine 250 b.h.p.; the power transmission efficiency is 85 per cent.

It will be seen that when the vessel is travelling at the first two speeds the *turbine is not running*, the whole of the necessary work being done by the engine, which runs at its top speed, and is then condensing; thus for slow vessel speeds, or for reversing, the minimum of steam is used. There is no necessity for the engineer to touch the engine, but all the electrical connections are changed by means of the controller, which may be either on the bridge or in the engine-room, as may be desired. At top speed, it is, however, necessary (either by hand or automatically) to turn the exhaust from the engine to the turbine, and from the turbine to the condenser. For reversing, only two out of the three phases of the conductors O need be reversed; the rotation of the engine and the turbine speeds are always in the same direction.

It will be of interest to describe another example which Durtnall has worked out[1] for employing only steam turbines as prime movers. The arrangement may be explained by reference to Fig. 39. The coupling from the steam turbine is A. The driven shaft is shown at B. It extends through the generator's revolving field-magnet C, and also drives the primary member of the transformer-generator D. On the shaft are also mounted slip-rings, K and G. The stator core of the generator is shown at E, and the stator winding at F. The winding of the primary member of the transformer-generator is shown at H; the stator secondary member of the transformer-generator is shown at I, and its winding at J, and the bedplate of the whole plant at L.

Working.—Assume that the steam turbine is running at 1000 r.p.m., and is capable of giving off 7000 b.h.p., working with a steam pressure of 180 lbs. per square inch, superheated by 150 degs. Fahr., exhausting into a vacuum of 28·5 ins. The generator C E is a synchronous polyphase alternator (three-phase), and the transformer-generator D I is wound for two poles on both primary and secondary members.

The exciting current can be drawn from the existing electric light

[1] See footnote on p. 144.

circuit, or may be supplied from a little continuous-current dynamo either direct-driven from the turbine shaft over-hung from the end of the transformer-generator, or separately driven by a small steam-engine.

FIRST SPEED AHEAD.—The controller (not shown here) is set at the notch marked "Ahead 1st." This so couples the alternator that

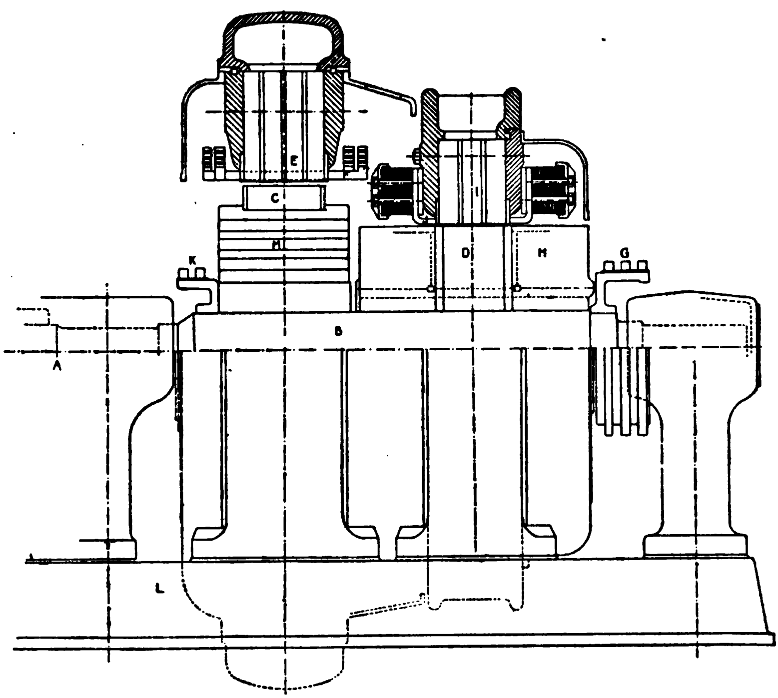


FIG. 39.—Durtnall's "Paragon" System Generating Unit for Three Frequencies and Motor Speeds.

when the current comes from the armature winding F, it goes into the winding marked H, forming the primary member of the transformer-generator, in such a way that on putting the exciting current on the slip-rings K (which are connected with the revolving magnet windings marked M), the current flows in the primary-member windings H. The resultant magnetic flux revolves in the iron in the opposite direction to that in which it is being driven mechanically by the turbine. Since it is a 4-pole generator, and since the winding H is

arranged for only 2 poles, it follows that for every turn "mechanically" in, say, the clockwise direction, the magnetic poles in the member D revolve counter-clockwise *twice*. The effect is that the winding in the stator I receives a transformed current corresponding to *two* poles at 1000 r.p.m., and consequently the current that can be taken from the secondary winding J has a frequency of 16·7 cycles per second. This current being at the time (by means of the controller) coupled to the lines leading to the squirrel-cage induction motor, which is wound for 42 poles, will then start with a powerful torque, and run in the ahead direction, at a speed (allowing 1½ per cent. for magnetic slip) of 46·8 r.p.m. The motor secondary member or rotor is direct coupled to a propeller shaft.

Second Speed Ahead.—By removing the exciting current from the slip-rings K, the whole system falls to zero voltage, and while in that condition the controller is placed in the notch marked "Second Speed Ahead." This means that the windings F of the armature member of the alternator are coupled direct to the motor stator windings, and by letting on the exciting current the frequency of the current going to the motor is then equal to 33·3 cycles per second, or the motor accelerates in speed from, say, 46·5 r.p.m. to 92·8 r.p.m. (allowing 2½ per cent. magnetic slip, as the loads will then be greater).

Third Speed Ahead.—By cutting off the exciting current, (which is arranged for automatically in the control gear), the system falls to zero voltage as before, and then, by placing the controller in the notch marked "Third Speed Ahead," the connections are so arranged by the controller that the current from the alternator windings F are again connected to the slip-rings G, but in this case *two* out of the *three* phases are reversed, so that on admitting the exciting current to the magnet windings C, through slip-rings K, the current in the windings of the primary member H causes the resultant magnetic flux to revolve in the iron in the same way that it is being driven "mechanically." Thus for every clockwise revolution of the turbine, the windings in the stator secondary member J are excited *twice* electro-magnetically, and *once* by means of the mechanical turn since it is wound for two poles. The current that can be drawn from the windings J has a frequency of 50 cycles per second. Since the motor stator windings are coupled to this supply, the

motor accelerates in speed from 92·8 r.p.m. to 138 r.p.m., which is the top speed (allowing 3½ per cent. for magnetic slip).

Reverse.—If it is desired to immediately reverse the speed direction of the propeller, this may be attained by first bringing the controller to the neutral point or notch marked "Stop," and then placing the controller lever in the notch marked "First Speed Astern." This means that *two* out of the *three* phases leading to the motor are reversed, and that the 16·7-cycle current is then turned on the motor stator, so that, being of such low frequency, and the motor of such a large number of poles, a powerful torque is set up in the reverse direction. At the same time, a very powerful braking action is set up, because if the rotor or propeller has not already come to a standstill, the magnetic flux in the iron of the stator is travelling in the reverse direction at a speed of 47·6 r.p.m., so that the rotor bar-winding is then cutting lines of magnetic force in the leading direction, and the motor momentarily becomes a non-synchronous generator, the windings being short-circuited on themselves, producing a very powerful couple to the poles in the stator, thus tending to stop and then reverse the propeller, then accelerating it in the reverse direction. The same process is gone through as regards the middle and top-speed reverse as in the ahead direction, until the vessel is travelling at full-speed reverse.

It is interesting to note that all through the above operations the turbine is being run governed in the ahead direction, and at constant speed, utilizing steam with the maximum efficiency at all propeller speeds, whether in the ahead or the astern direction. The controller can be just as easily placed, if desired, on the bridge or in the engine-room, or it may be arranged for at other important positions.

Steam Consumption

At Full Power and Speed.—It may be taken that such a turbine will use, under the above conditions at sea, 9·8 lbs. of steam per shaft h.p.-hour. The overall mechanical efficiency of the combined generator and motor can be guaranteed to be not less than 90 per cent., so that at top speed the steam used per shaft h.p.-hour will, without auxiliaries, be 10·9 lbs., the total steam flow for propulsion thus being 68,600 lbs. per hour, and the output being 6300 shaft h.p.

MIDDLE SPEED.—If the shaft h.p. is 6300 at 138 r.p.m. of the propeller, it may be taken that at 92·8 r.p.m. the shaft h.p. will be in the neighbourhood of 1500, so the steam flow at the middle speed will be approximately as follows:—

Although the turbine is still running at the same revolution speed, it will not be delivering so much power, consequently the steam consumption per h.p.-hour output from the turbine will increase, as compared with that at full load, and the turbine will consume approximately 11·1 lbs. of steam per brake h.p.-hour. For this middle speed the current is taken direct from the alternating generator to the motor. The power transmission efficiency at this speed can be guaranteed to be not less than 85 per cent., consequently the steam consumption per shaft h.p.-hour will be 13·1 lbs. at this low power and revolution speed. The total steam flow at this vessel speed will be 19,700 lbs. per hour.

BOTTOM SPEED.—Assuming that, at 46·8 r.p.m., the shaft h.p. is, say, 600, the overall transmission efficiency will be approximately 79 per cent., and the steam consumption per h.p.-hour of output from the turbine will be about 13·8 lbs. Consequently, with a transmission efficiency of 79 per cent., the steam per shaft h.p. at this speed of revolution of the propeller will be 17·4 lbs. per hour, or a total steam flow of about 10,400 lbs. per hour.

Propellers

Mr. Durtnall has also investigated the properties of propellers, and has advanced some radical propositions in connection with this subject. He states that "not the least interesting item in connection with the electric propulsion of ships is the propeller. It is obviously one of the very most important components of the propulsive machinery. The screw propeller has been undergoing a process of development during the last fifty years, but although great advances have been made in its design and construction, it has not been able to develop an effective thrust for pushing boats of more than some 40 to 60 per cent. of the shaft h.p., and the efficiency is often even below this range of values. Thus the question of the efficiency of the propeller is a matter of the greatest importance, and affects the design not only of all other components

of the propulsive machinery, but also of the general outlines of the vessel itself. Just in so far as the efficiency of the propeller can be improved, so can lighter and smaller engines, and smaller capacity of boiler plant and auxiliaries, be employed. The amount of fuel may also be decreased, and the capacity of the bunkers. Thus, it is of great importance to obtain as high a propeller efficiency as is practicable. The economies incident to the adoption of the internal-combustion engine are of minor importance unless means of utilizing the engines' power are also of an efficient nature. The screw propeller has limitations as regards the revolution speed at which it may be run, with given blade area, to produce maximum thrust for propulsion per shaft h.p." It is in view of these circumstances that Durtnall is advocating the adoption of a radically novel propeller, which is now being introduced in connection with the Paragon system of ship propulsion. Durtnall considers this propeller to be especially suitable in connection with *electrical* propulsion, and he claims that when it is used in this connection "a much higher thrust per h.p. can be produced than by any other method." The "Paragon" steering and reversing marine propeller may be explained by reference to Fig. 40. Durtnall describes it as consisting of "a rotary method of feathering a paddle wheel, which runs at work right down almost level with the keel of the boat, thus taking advantage of the extra depth of water. As a result, this propeller can be run, for a given amount of thrust per shaft h.p., at about three to four times the revolution speed of a screw propeller for similar duty. An interesting and important feature of the propeller is that it also answers in a very efficient way both for steering and reversing, and without altering the direction of revolution of the propeller." This control can be brought about by means of ordinary steering gear, and Durtnall states that ships so fitted may be handled with great certainty and reliability. Tests carried out with this propeller are stated to show that it can be run at as high a speed as 2000 r.p.m. without the least sign of cavitation, and with high effective thrust per h.p. Furthermore, the stream lines given off are in a horizontal direction, and not in the fan-shaped waves shown by screw propellers. A consequence is that vessels fitted with the "Paragon" propeller are able to proceed in narrow waterways at greater speed than would be practicable with screw propellers, because

the banks, as also any other craft on the water, will be more immune from damage. The "Paragon" propeller would appear to be especially suitable for electric propulsion, since with the much higher revolution speed the induction motor which drives it will be lighter, smaller, lower in cost, and of higher efficiency than induction motors of the same output but designed for driving slow-speed screw propellers. The operation of the "Paragon" propeller is (referring to Fig. 40) as follows: C is a vertical, hollow shaft, on which

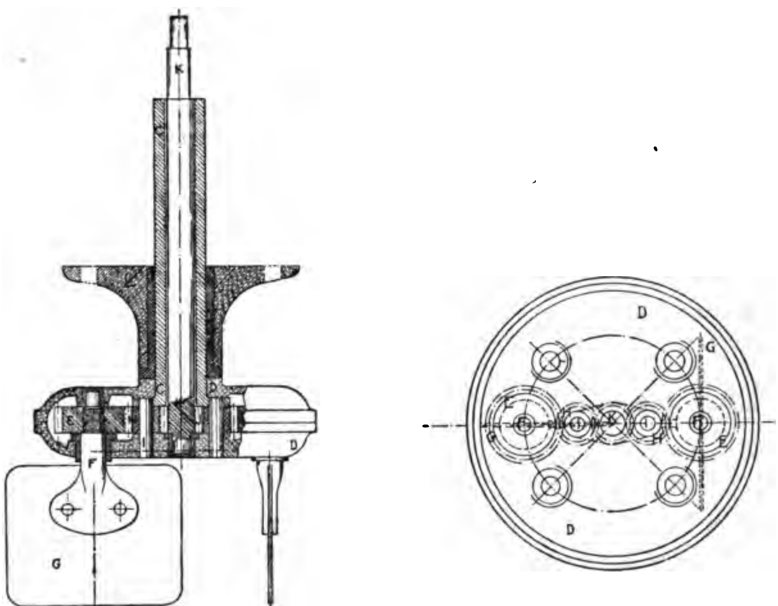


FIG. 40.—"Paragon" Steering and Reversing Marine Propeller specially designed for Electrical Driving by means of Vertical Induction Motor.

can be mounted a vertical-type induction motor (not shown in the figure). D is a case containing the set of feathering wheels. These run in grease, and are driven at the same speed as the motor. It will be observed that the torque from the motor is delivered direct to the bearings carrying the propeller blades. E is one of two or more wheels which feather the blades, through the shaft F, to which the blades G are coupled (the propeller shown having two blades). H is a small, loose, intermediate wheel, which allows the feathering to take place in a rotary manner and in the right direction. It runs

on the spindle I, and is also geared to J, which is a pinion carried by the vertical shaft K, and having just half as many teeth as there are in E. Consequently, the blades make half a turn for one complete turn of the drum D. The pinion J is held still by means of the steering gear of the boat, which is similar to that employed for a boat steered with a rudder. This enables the wheels E to run round it, thus imparting the feathering motion to the blades. The centre pinion J is usually in a stationary condition; by its means, however, the degree of feathering is adjusted, which determines whether the reaction from the propeller shall be ahead or astern. The position of J is controlled through the shaft K by means of the steering wheel. The main bearing, which also takes the total thrust produced, is marked L, and is bolted direct to the vessel's stern or side, as the case may be. The "Paragon" propeller was the subject of interesting comments on the occasion of the discussion of Mr. Durtnall's paper on "The Internal-Combustion Engine," read at the September 17, and November 28, 1910, meetings of the Institute of Marine Engineers.

The Alter-Phase Multi-Frequency Generator

In the earlier sections of this chapter, Mr. Durtnall's plan for obtaining a considerable range of frequencies has been described. British patent No. 30556 of 1909, granted to Mr. Mavor and myself (and to which reference has already been made in Chapter XIV.), discloses another method of accomplishing the same object. It is based upon an application of the alter-phase principle. By this method the number of different periodicities which can be obtained and supplied to the motor or motors can be greater than the number of component generators. The several component generators can, when appropriate, be driven from the same shaft. For explaining the method, the example may be taken of two components of a multi-frequency generator, which are driven at, say, 600 r.p.m. Let the primary component comprise an internal revolving field with 10 poles, and be excited with continuous electricity. The stator of this primary component may have two independent windings supplying respectively three-phase and quarter-phase electricity. As an alternative, the stator may have a quarter-phase winding, and the three-

phase electricity required for the purposes of the method may be obtained by means of stationary transformers, as shown diagrammatically in Fig. 41, which illustrates the Scott connection for converting from quarter-phase to three-phase electricity. As a further alternative which may be mentioned, the stator of the primary component of the generating set may, instead of having two distinct windings, the one quarter-phase and the other three-phase, be provided with a 10-pole winding of the lap type, and this winding may have 15 equidistant taps, which, suitably grouped, will constitute a source of three-phase electricity, and it may have a further set of 20 equidistant taps which, suitably grouped, will constitute a source

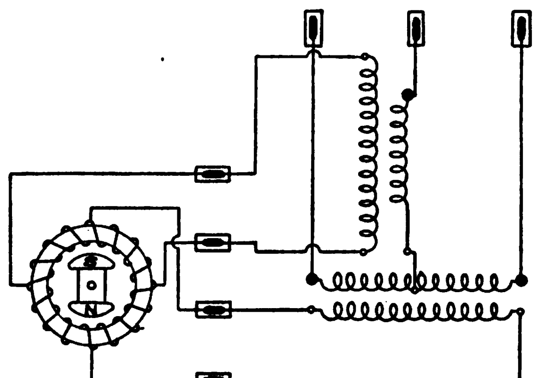


FIG. 41.—The Scott Connection.

of quarter-phase electricity. The secondary component of the generating set is of the construction commonly employed for induction motors. In this instance, we will consider that the rotor of this secondary component is mounted on the same shaft as the rotor of the primary component. The electricity supplied by the primary component may be first led to either the stator or the rotor of the secondary component. Let us consider that in the present case the electricity from the primary component is taken to the *stator* of the secondary component. This stator is provided with a winding which, when suitably connected, constitutes a three-phase, 8-pole winding, and which, by means of suitable simple circuit changes, can be readily altered into an equally effective 6-pole, quarter-phase

winding. The general plan is indicated diagrammatically in Fig. 42. In this figure, C represents the internal revolving field of the primary component, and it is excited by continuous electricity, which is supplied to its windings by means of the slip-rings D. E is the stator, electricity from which is received by a circuit, F, and conducted by a reversing switch, G, to the stator H of the secondary component, the rotor I of which is mechanically coupled to the rotor C. Other numbers of poles might have been selected, not only for the primary component, but also for the secondary component. Furthermore,

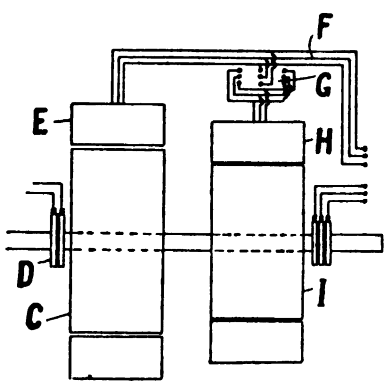


Fig. 42.—Diagram of Alter-Phase Multi-Frequency Generator.

other systems of phases may be employed. In the present example, the primary component has a periodicity of—

$$\frac{600}{60} \times \frac{10}{2} = 50 \text{ cycles per second.}$$

When the supply is three-phase, then the secondary component's windings are arranged for 8 poles, and when the electricity is supplied from the primary component as quarter-phase, the secondary component's windings are arranged for 6 poles. Corresponding changes may be effected in the secondary component's rotor I, which may have its windings grouped for 8 poles or for 6 poles, in accordance with the operation of any suitable change-control means, such as (see Fig. 43) a sliding collar, J, on the shaft, moved, as by a lever, K, into the one or the other of two positions as indicated in Fig. 43. Obviously the two positions of the collar J may be arranged to make two different sets of circuit connections. The precise arrangement

indicated in Fig. 43 is merely given for purposes of explanation, since it would not be suitable for large machines, but there are various well-known ways of effecting the desired circuit changes. As an alternative, the rotor of the secondary component may be

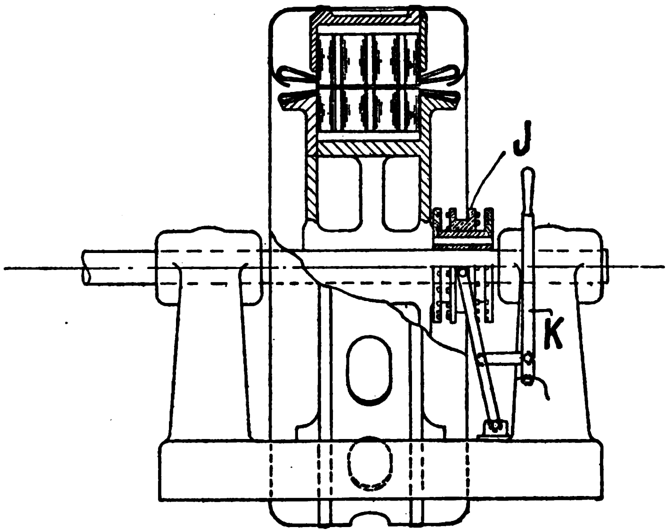


FIG. 43.—Secondary Component of Alter-Phase Multi-Frequency Generator.

provided with a lap winding, preferably with a pitch of about one-seventh. If suitable taps are taken from this winding to collector rings, then, according to requirements, the rotor will have 8 or 6 poles. In the example above described, a generating set providing five different periodicities is obtained. These periodicities correspond to the following table :—

Number of poles.		Sum or difference.	Equivalent total number of poles.	Periodicity at 600 r.p.m.
Prim. Gen.	Sec. Gen.			
10	8	sum	18	90
10	6	sum	16	80
10	—	—	10	50
10	6	difference	4	20
10	8	difference	2	10

CHAPTER XVI

THE EMMET SYSTEM OF SHIP PROPULSION

CERTAIN methods of employing electricity in ship propulsion have been worked out by Mr. W. L. R. Emmet, and are described and illustrated in two recent papers. The first is entitled, "Applications of Electricity to the Propulsion of Naval Vessels," and was read at a meeting of the Society of Naval Architects and Marine Engineers, held in New York on November 18 and 19, 1909. The second paper is entitled, "Proposed Applications of Electric Ship Propulsion," and was presented at the Pittsfield-Schenectady mid-year convention of the American Institute of Electrical Engineers, held on February 14, 15, and 16, 1911.

A certain broad point of view runs through Mr. Emmet's propositions, and distinguishes them from the propositions of other workers in this field. In the case of a battleship, where, as we have seen, the cruising speed is only some 60 per cent. of the maximum speed, but which may often be required to travel at any speed between cruising and maximum speed, Mr. Emmet does not attempt to provide speed variations by electrical methods, except to the extent of having two fundamental speeds provided by two fundamental winding arrangements of the induction motors which drive the propeller shafts. All speeds other than these two fundamental speeds are obtained by simply changing the steam admission, and thus operating the generating sets at different speeds. In the first paper to which reference has been given, Mr. Emmet works out an equipment for a battleship of 20,000 tons displacement, which is to have a maximum speed of 20·5 knots, and a cruising speed of 12 knots. The turbo-generators are controlled (by changing the steam admission) to run, according to the result desired, at speeds ranging between a minimum of 830 revolutions per minute, and a maximum of 1300 r.p.m. Thus

the speed of the ship is varied through a considerably wider range than the corresponding speed of the turbo-generators. Indeed, the cruising speed of 12 knots, which is the most important speed as regards economy, is obtained with a speed of 1105 r.p.m. of the turbo-generators, as against a speed of 1172 r.p.m. for the maximum speed of the ship, *i.e.* 20·5 knots. The lowest speed of the turbo-generators, *i.e.* 830 r.p.m., is only employed at the intermediate speed of 15 knots, which would seldom be required, and for which high economy is of less importance. By only having two arrangements of windings of his motors, Mr. Emmet gains the advantage of a high degree of simplicity in electrical control; and he makes no material sacrifice in obtaining this advantage, since a reasonable amount of alteration of the speed of the steam turbines is not incompatible with good economy.

Mr. Emmet further improves the economy by resort to the obvious means employed in other systems already described, namely, of improving the load factor by shutting down part of the generating plant at light loads. In the particular case referred to, the arrangement for various speeds is as follows:—

Speed in knots.	Shaft h.p.	No. of poles of motors.	Motor efficiency (in per cent.).	Motor power factor.	Generator speed (r.p.m.).	Motor speed (r.p.m.).	Vacuum in inches.	No. of generators in circuit.	No. of motors in circuit.	Pounds of water per shaft h.p.-hr.
12	4400	50	97·5	0·60	1105	131	28·5	1	2	12·3
14	6900	50	95	0·65	1295	153	28·2	1	2	11·8
15	8600	30	96	0·83	830	164	27·5	1	2	12·6
15	8600	30	96	0·79	830	164	28·2	2	4	13·4
18	15350	30	96	0·84	1005	198	27·8	2	4	12·3
20	22700	30	96	0·85	1130	224	27·3	2	4	12·1
20·5	26000	30	96	0·85	1172	232	27·0	2	4	12·3

In working out this equipment, the same propeller speed was employed (for purposes of comparison) as for a battleship of the same displacement and speed, but for which a direct drive by Curtis steam turbines had been proposed. If the motor speeds had been taken still lower, the propeller efficiency could have been increased, and "the net result would have been improved without serious increase in weight."

The second feature in which Mr. Emmet departs from the usual programme is in employing slip-ring rotors in two of his four induction motors. At the maximum speed, each of the two propeller shafts is driven by two motors. One has a squirrel-cage rotor, and is so wound that it may be connected for either 30 or 50 poles. This motor, and its duplicate on the other shaft, are alone in circuit at the lowest speeds (12 to 15 knots). At higher speeds, not only are these two squirrel-cage motors in circuit, but two motors, wound for 30 poles and provided with slip-ring rotors, are also employed, one on each shaft. Since these additional motors are not required at the lower speeds (because the power decreases as the cube of the speed), there is no need to arrange a 50-pole connection for them. As they are not required to have two different numbers of poles, no special complication is involved in providing them with a "wound" rotor and with slip-rings. By means of the slip-rings, external resistances are connected in the rotor circuits, in order to imbue the motors with powerful torque attributes for occasions when it is required to reverse the propellers. By means of this feature it will become practicable to stop or reverse a ship much more quickly than with the direct drive by steam turbines. Thus, while at first glance the reader might be inclined to deny novelty to Mr. Emmet's arrangement, a closer consideration reveals an appropriateness and purpose in the various components which, in spite of its simplicity, distinguish it clearly from the arrangements employed by other workers in the field.

Mr. Emmet gives the following weights for parts of the equipment described:—

2 squirrel-cage motors with pole-changing switches	63·5 tons
2 slip-ring 30-pole motors	60·0 „
Switches, levers, supports, etc.	2·7 „
Cables, 'busses, supports, etc.	1·8 „
Rheostats	1·3 „
2 generators	125·0 „
2 Curtis turbines, exclusive of bearings	97·4 „
Ventilating accessories	3·1 „
Total	354·8 „

A tender had been put in for a direct drive with Parsons turbines, and the corresponding parts of the equipment came to 485

tons. This weight does not include any piping, bearings, shafting, valves, or auxiliaries. The electric drive proposed by Mr. Emmet thus saves 130 tons. Mr. Emmet points out that "the piping system necessary with the Parsons turbine equipment is very complicated, and the weight of steam and exhaust piping and valves given in the Navy Department's estimates amounts to 76·5 tons. With the electric drive only one steam-pipe connection is necessary inside of the engine-room." Mr. Emmet was of opinion that the saving of piping inside the engine-room alone would amount to "at least 40 tons" in the electric system. The weight of the boilers corresponding to the direct drive was 555 tons, and since Mr. Emmet's comparisons indicate a steam consumption at 20·5 knots of only 12·3 lbs. per b.h.p.-hr. by the electric system, as against 13·9 lbs. per b.h.p.-hr. for the Parsons direct drive, he claimed that a reduction of boiler weights would also attend the use of the electric drive. The steam consumption for the two systems is given in the following table:—

Speed in knots.	Pounds of steam per b.h.p.-hour for—	
	Electric drive.	Parsons drive.
12	12·3	20·2
14	11·8	17·5
15	12·6	16·5
18	12·3	14·7
20	12·1	14·0
20·5	12·3	13·9

The decrease in required boiler capacity is not in the ratio of 13·9 to 12·3 (the steam consumptions per b.h.p.-hr. at the 20·5 knot speed), but is affected by the steam required for "all uses outside the main prime movers," which is taken at 26,300 lbs. per hour when the vessel is travelling at the cruising speed of 12 knots. Mr. Emmet works out the increase in cruising radius at 68 per cent. for the 12-knot speed when he decreases the weight of boilers commensurately with the above data, and adds the saving to the original bunker capacity of 2476 lbs. of coal.

In the discussion on the paper the question of cost was raised. Mr. Emmet gave the following interesting information. He stated that it was the experience of his company "that the cost of building

land turbines is not very different per pound from that of the generators which they drive." He points out that it follows that, "pound for pound," his "combination is not very much more expensive to build than a straight turbine drive." He then continues: "I will say, roughly, that some of our large turbine apparatus—a great deal of it, I think, throughout the country—is sold somewhere in the neighbourhood of 20 cents a pound. The weight of this equipment has been given, and you can figure approximately what it might cost. However, this being a special thing, and there being a good deal of special adaptation in connection with it, it might run a good deal higher." Mr. Emmet's figure of 20 cents per pound comes to 1·76 shilling per kilogram, or £88 per ton. Thus, if we take £110 per ton, then the cost of the portions listed in the table on p. 160 would work out at—

$$355 \times 110 = £39{,}000,$$

or $\frac{39000}{26000}$ = £1·5 per shaft h.p. for turbo-generators, motors, switches, rheostats, and cables, but exclusive of boilers, condensers, piping, and numerous auxiliaries. Thus the £1·5 per shaft h.p. is for but a portion of the total required machinery.

In the second of the papers mentioned on p. 158, Mr. Emmet describes a similar equipment, worked out for motor speeds only about seven-tenths of the speeds in the equipment above described, reduced to the same vessel speeds. In this equipment the weight of the four motors is stated to be 182 tons, which is just about in inverse proportion to the speeds in the two cases.

Of course, in all such preliminary investigations the premises employed necessarily affect the results. Thus the type and amount of ventilation employed is of predominating influence. I have called attention to these rough data of weight and cost simply to indicate the general order of magnitude appropriate to such a case.

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